XVI Escola Jorge Swieca

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

Our Picture of Matter

Pointlike constituents ($r < 10^{-18}$ m)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

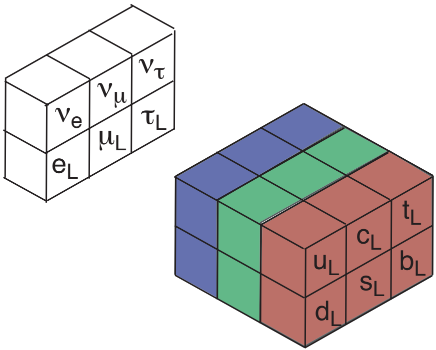
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Few fundamental forces, derived from gauge symmetries

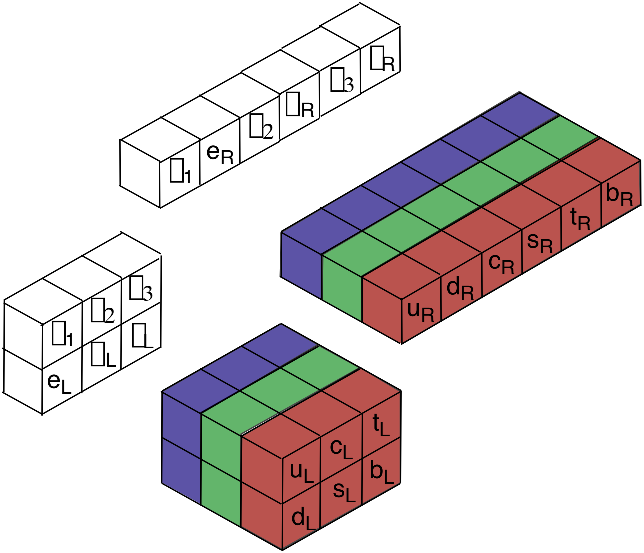
$$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$$

Electroweak symmetry breaking: Higgs mechanism?

Our Picture of Matter



Our Picture of Matter



Quantum Chromodynamics: Yang-Mills theory for $SU(3)_c$

Single quark flavor:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m)\psi - \tfrac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu})$$

composite spinor for color-**3** quarks of mass m

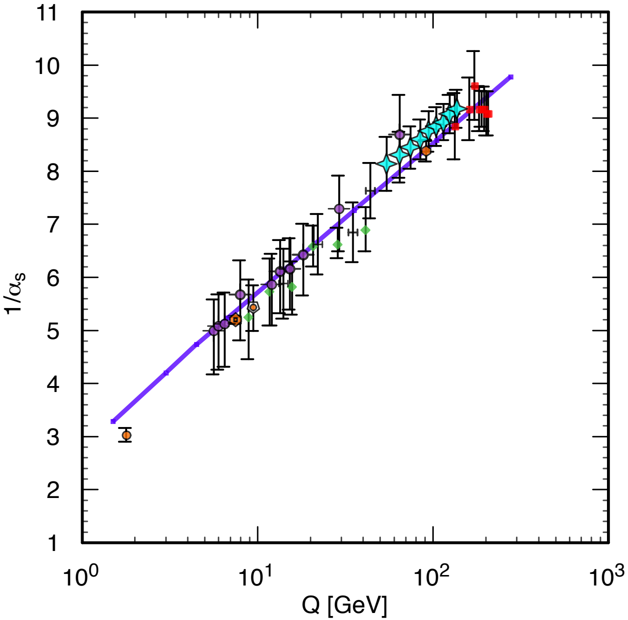
$$\psi = \begin{pmatrix} q_{\text{red}} \\ q_{\text{green}} \\ q_{\text{blue}} \end{pmatrix}$$

Gauge-covariant derivative:

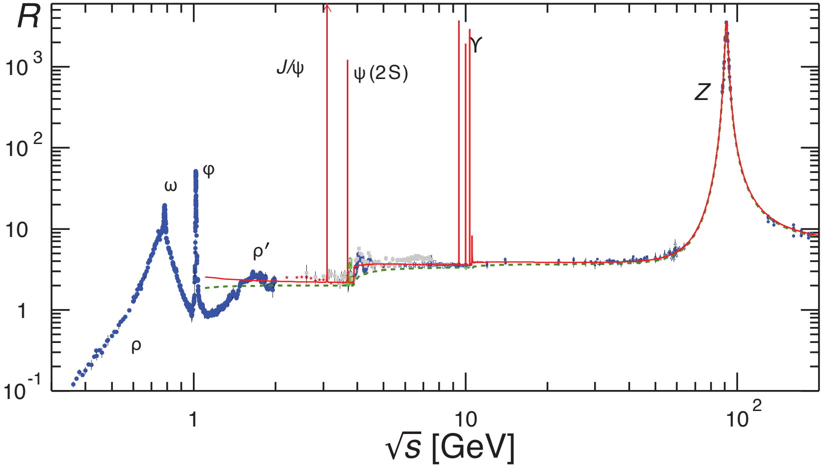
$$\mathcal{D}_\mu = I\partial_\mu + igB_\mu$$

g: strong coupling; B_μ: 3×3 matrix in color space formed from 8 gluon fields B_μ^ℓ and $SU(3)_c$ generators $\frac{1}{2}\lambda^\ell$ ...

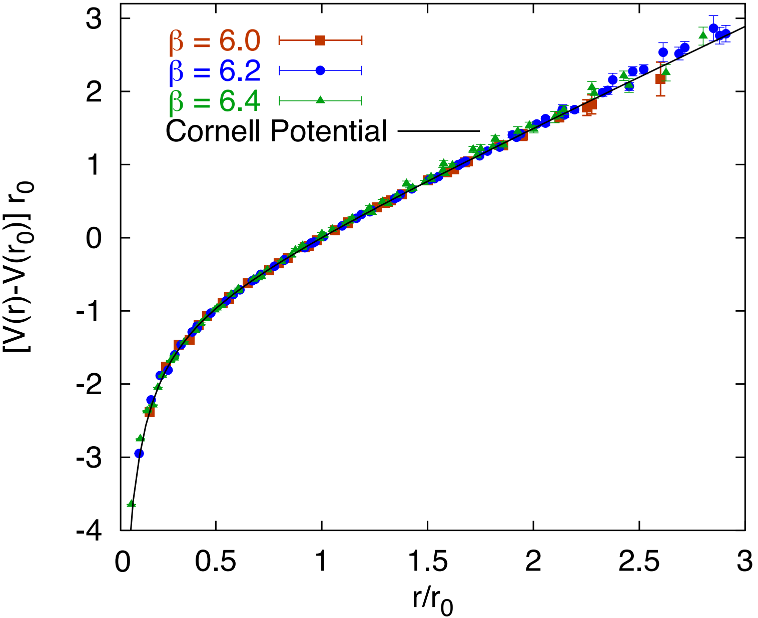
QCD Tests: Asymptotic Freedom



QCD Tests: $e^+e^- \to$ hadrons



QCD Tests: Quark Confinement



A theory of leptons

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \mathsf{R} \equiv e_R$$

weak hypercharges $Y_L = -1$, $Y_R = -2$

Gell-Mann–Nishijima connection, $Q = I_3 + \frac{1}{2}Y$

$\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ gauge group $\Rightarrow$ gauge fields:

- weak isovector $\vec{b}_\mu$, coupling g $\quad \boxed{b_\mu^\ell = b_\mu^\ell - \varepsilon_{jk\ell}\alpha^j b_\mu^k - (1/g)\partial_\mu \alpha^\ell}$
- weak isoscalar $\mathcal{A}_\mu$, coupling $g'/2$ $\quad \boxed{\mathcal{A}_\mu \to \mathcal{A}_\mu - \partial_\mu \alpha}$

Field-strength tensors

$$F_{\mu\nu}^\ell = \partial_\nu b_\mu^\ell - \partial_\mu b_\nu^\ell + g\varepsilon_{jk\ell} b_\mu^j b_\nu^k \qquad \mathrm{SU(2)_L}$$

$$f_{\mu\nu} = \partial_\nu \mathcal{A}_\mu - \partial_\mu \mathcal{A}_\nu \qquad \mathrm{U(1)_Y}$$

Interaction Lagrangian

$$\boxed{\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{leptons}}}$$

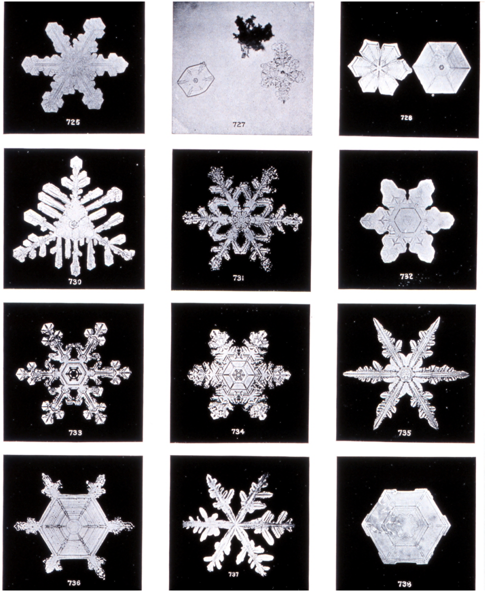
$$\mathcal{L}_{\text{gauge}} = -\tfrac{1}{4}F^{\ell}_{\mu\nu}F^{\ell\mu\nu} - \tfrac{1}{4}f_{\mu\nu}f^{\mu\nu},$$

$$\begin{aligned}\mathcal{L}_{\text{leptons}} &= \overline{\mathsf{R}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y\right)\mathsf{R} \\ &+ \overline{\mathsf{L}}\, i\gamma^{\mu}\left(\partial_{\mu} + i\frac{g'}{2}\mathcal{A}_{\mu}Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_{\mu}\right)\mathsf{L}.\end{aligned}$$

Mass term $\mathcal{L}_e = -m_e(\bar{e}_{\mathsf{R}}e_{\mathsf{L}} + \bar{e}_{\mathsf{L}}e_{\mathsf{R}}) = -m_e\bar{e}e$ violates local gauge inv.

Theory: 4 massless gauge bosons ($\mathcal{A}_{\mu}$ b^1_{μ} b^2_{μ} b^3_{μ}); Nature: 1 (γ)

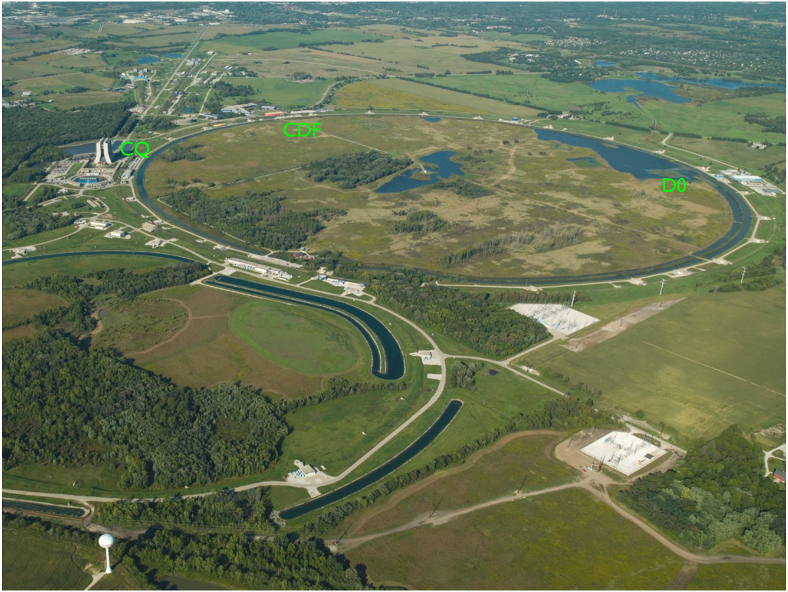
Symmetry of laws $\not\Rightarrow$ symmetry of outcomes



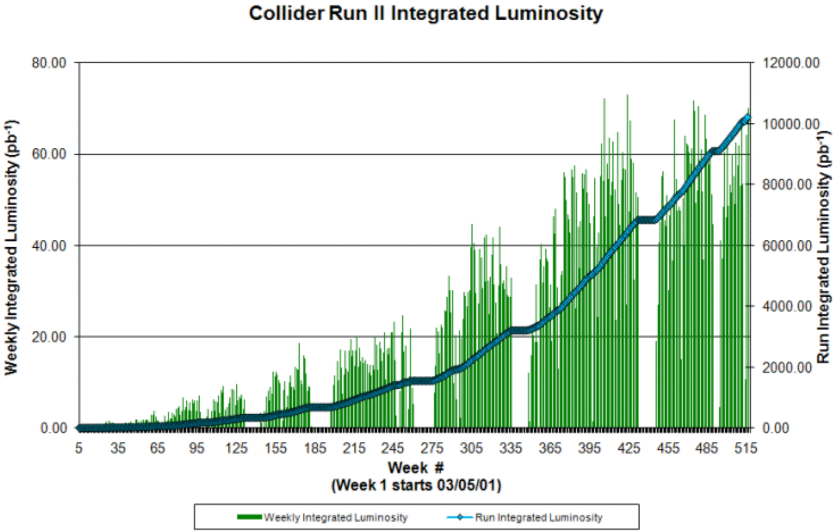
A Decade of Discovery Past

- ▷ Electroweak theory validated [Z, e^+e^-, $\bar{p}p$, νN, ...]
- ▷ Higgs-boson influence observed [EW experiments]
- ▷ Neutrino oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \to B\bar{B}$]
- ▷ Flat U, mostly dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Constituents structureless at TeV scale [mainly colliders]

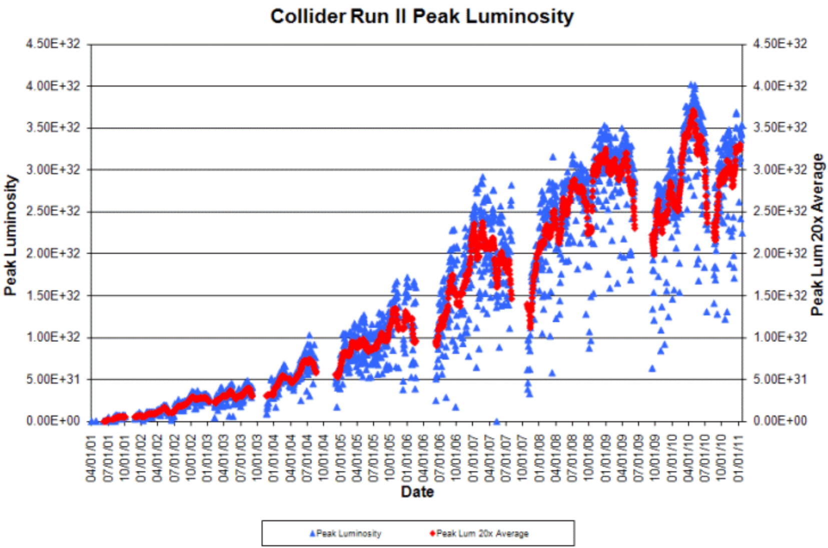
Tevatron: $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV



Tevatron Performance



Tevatron Performance



Tentative Program

1. Lecture 1
2. Lecture 2
3. Lecture 3
4. Lecture 4
5. Lecture 5

Topic 1: The Setting

Unanswered Questions in the Electroweak Theory

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Key Words

electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

Abstract

This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

Electroweak theory antecedents

Lessons from experiment and theory

- Parity-violating $V - A$ structure of charged current
- Cabibbo universality of leptonic and semileptonic processes
- Absence of strangeness-changing neutral currents
- Negligible neutrino masses; left-handed neutrinos
- Unitarity: four-fermion description breaks down at $\sqrt{s} \approx 620$ GeV $\qquad \nu_\mu e \to \mu \nu_e$
- $\nu\bar{\nu} \to W^+W^-$: divergence problems of *ad hoc* intermediate vector boson theory

Electroweak theory consequences

- Weak neutral currents
- Need for charmed quark
- Existence and properties of $W^{\pm}$, Z^{0}
- No flavor-changing neutral currents at tree level
- No right-handed charged currents
- CKM Universality
- KM phase dominant source of CP violation
- Existence and properties of Higgs boson
- Higgs interactions determine fermion masses, *but . . .*
- (Massless neutrinos: no neutrino mixing)

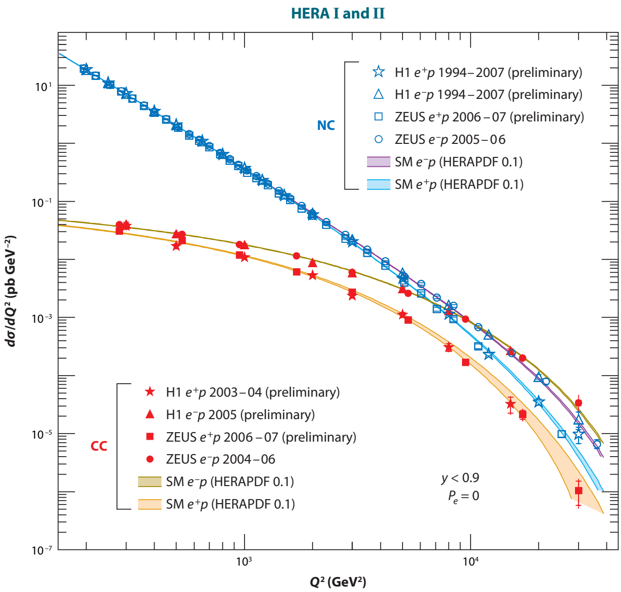
Electroweak theory tests: tree level

- $W^{\pm}$, Z^0 existence and properties verified
- Z-boson chiral couplings to quarks and leptons agree with $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ theory
- Third generation of quarks and leptons discovered
- Constraints on a fourth generation
- $M_{Z'} \gtrsim 789$ GeV (representative cases)
- $M_{W'} \gtrsim 1000$ GeV
- $M_{W_\mathrm{R}} \gtrsim 715$ GeV, $g_\mathrm{L} = g_\mathrm{R}$
- Strong suppression of FCNC:

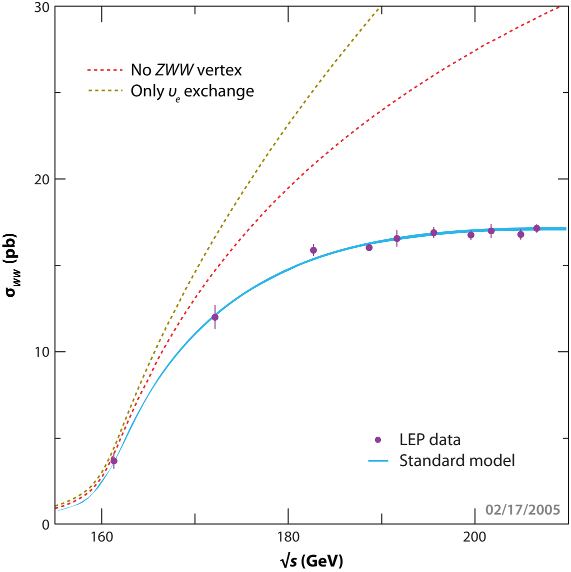
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10};$$

$$\text{SM expectation} = (0.85 \pm 0.07) \times 10^{-10}$$

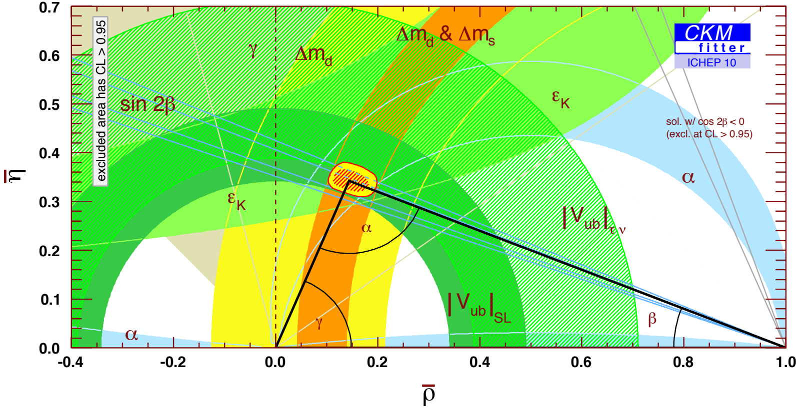
Electroweak theory tests: tree level



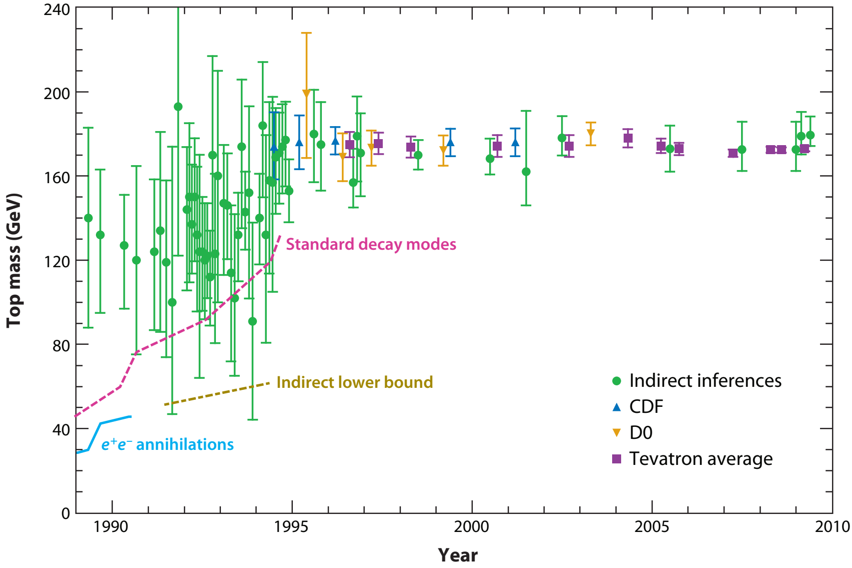
Electroweak theory tests: tree level



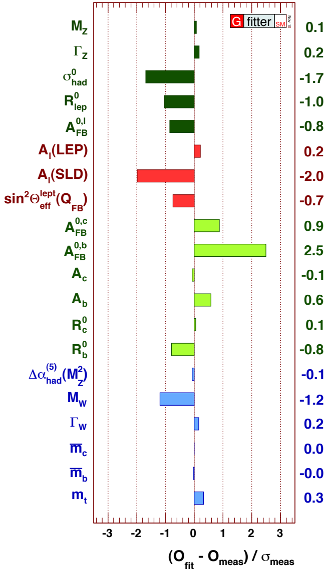
Electroweak theory tests: CKM paradigm



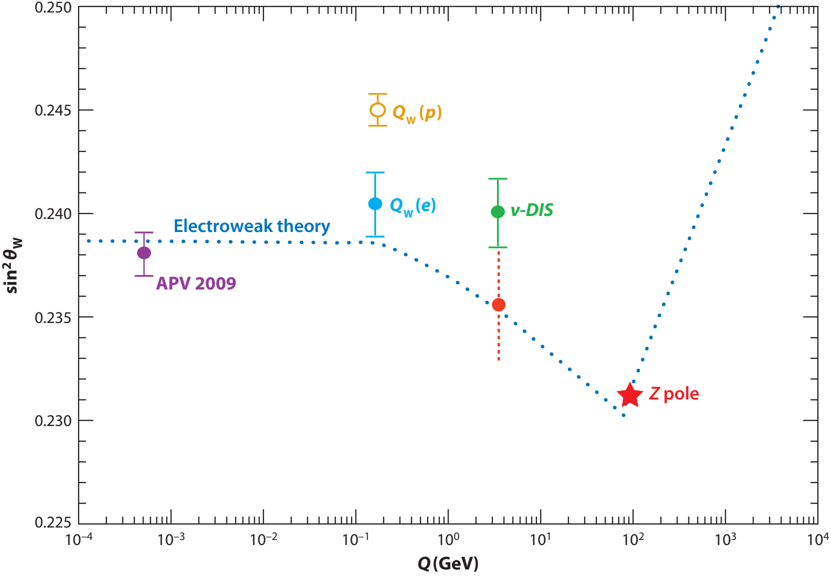
Electroweak theory tests: loop level



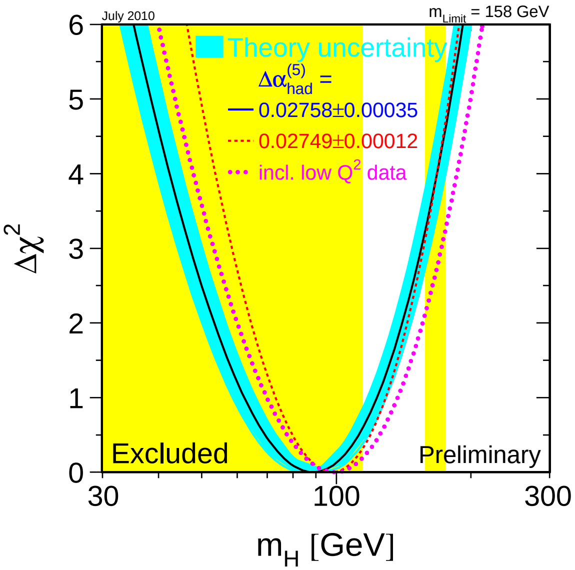
Electroweak theory tests: loop level



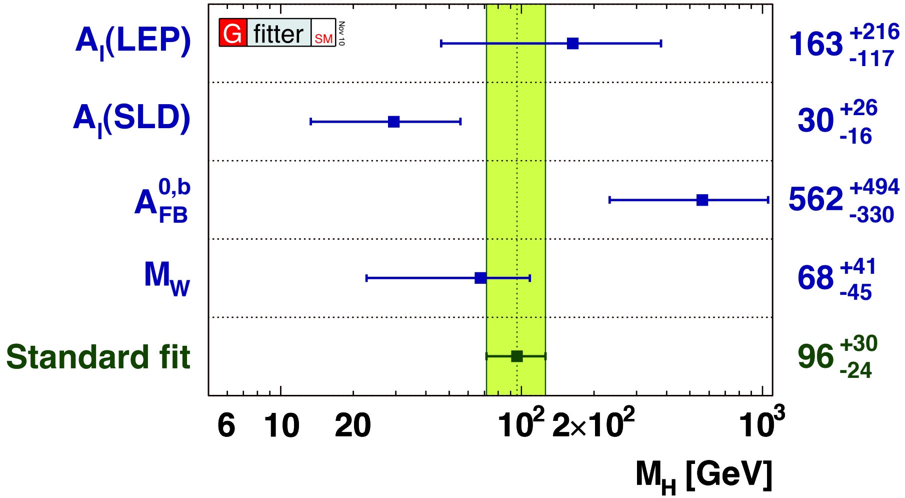
Electroweak theory tests: low scales [Z']



Electroweak theory tests: Higgs influence



Electroweak theory tests: Higgs consistency?



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Electroweak theory successes

$\rightsquigarrow$ search for agent of EWSB

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Spontaneous symmetry breaking as a basis of particle mass

Chris Quigg

Higgs (then)

Kibble, Guralnik, Hagen, Englert, Brout (2010)

1-TeV Scale

Hiding EW Symmetry

Higgs mechanism: relativistic generalization of Ginzburg-Landau superconducting phase transition

- Introduce a complex doublet of scalar fields

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad Y_\phi = +1$$

- Add to $\mathcal{L}$ (gauge-invariant) terms for interaction and propagation of the scalars,

$$\mathcal{L}_{\text{scalar}} = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) - V(\phi^\dagger \phi),$$

where $\mathcal{D}_\mu = \partial_\mu + i\frac{g'}{2}\mathcal{A}_\mu Y + i\frac{g}{2}\vec{\tau} \cdot \vec{b}_\mu$ and

$$\boxed{V(\phi^\dagger \phi) = \mu^2 (\phi^\dagger \phi) + |\lambda| (\phi^\dagger \phi)^2}$$

- Add a Yukawa interaction $\mathcal{L}_{\text{Yukawa}} = -\zeta_e \left[\overline{\mathsf{R}}(\phi^\dagger \mathsf{L}) + (\overline{\mathsf{L}}\phi)\mathsf{R}\right]$

- Arrange self-interactions so vacuum corresponds to a broken-symmetry solution: $\mu^2 < 0$
  Choose minimum energy (vacuum) state for vacuum expectation value

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad v = \sqrt{-\mu^2/|\lambda|}$$

Hides (breaks) $SU(2)_L$ and $U(1)_Y$

but preserves $U(1)_{\text{em}}$ invariance

Invariance under $\mathcal{G}$ means $e^{i\alpha\mathcal{G}}\langle\phi\rangle_0 = \langle\phi\rangle_0$, so $\mathcal{G}\langle\phi\rangle_0 = 0$

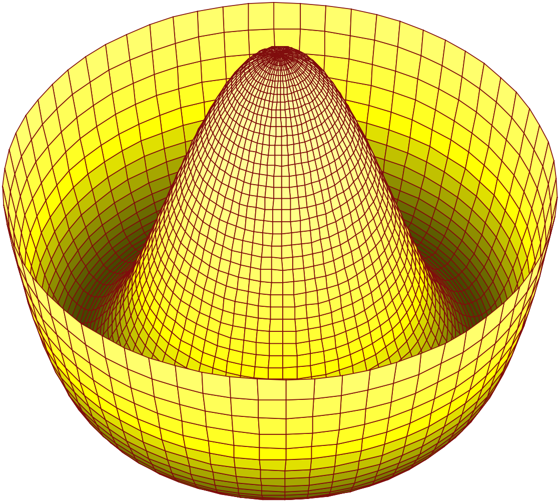
$$\tau_1\langle\phi\rangle_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_2\langle\phi\rangle_0 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} -iv/\sqrt{2} \\ 0 \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$\tau_3\langle\phi\rangle_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} = \begin{pmatrix} 0 \\ -v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

$$Y\langle\phi\rangle_0 = Y_\phi\langle\phi\rangle_0 = +1\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \neq 0 \quad \text{broken!}$$

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes



Examine electric charge operator Q on the (neutral) vacuum

$$
\begin{aligned}
Q\langle\phi\rangle_0 &= \tfrac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 \\
&= \tfrac{1}{2}\begin{pmatrix} Y_\phi + 1 & 0 \\ 0 & Y_\phi - 1 \end{pmatrix}\langle\phi\rangle_0 \\
&= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \\
&= \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \textit{unbroken!}
\end{aligned}
$$

Four original generators are broken, *electric charge is not*

- $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to U(1)_{\mathrm{em}}$ (will verify)
- Expect massless photon
- Expect gauge bosons corresponding to

$$\tau_1,\ \tau_2,\ \tfrac{1}{2}(\tau_3 - Y) \equiv K \quad \text{to acquire masses}$$

Expand about the vacuum state

Let $\phi = \begin{pmatrix} 0 \\ (v+\eta)/\sqrt{2} \end{pmatrix}$; in *unitary gauge*

$$\begin{aligned} \mathcal{L}_{\text{scalar}} &= \tfrac{1}{2}(\partial^\mu \eta)(\partial_\mu \eta) - \mu^2 \eta^2 \\ &\quad + \frac{v^2}{8}[g^2 \left| b_\mu^1 - i b_\mu^2 \right|^2 + (g' \mathcal{A}_\mu - g b_\mu^3)^2] \\ &\quad + \text{interaction terms} \end{aligned}$$

"Higgs boson" η has acquired (mass)^2 $M_H^2 = -2\mu^2 > 0$

$$\text{Define } W_\mu^\pm = \frac{b_\mu^1 \mp i b_\mu^2}{\sqrt{2}}$$

$$\frac{g^2 v^2}{8}(\left|W_\mu^+\right|^2 + \left|W_\mu^-\right|^2) \Longleftrightarrow M_{W^\pm} = gv/2$$

$$(v^2/8)(g'\mathcal{A}_\mu - g b^3_\mu)^2 \ldots$$

Now define orthogonal combinations

$$Z_\mu = \frac{-g'\mathcal{A}_\mu + g b^3_\mu}{\sqrt{g^2 + g'^2}} \qquad A_\mu = \frac{g\mathcal{A}_\mu + g' b^3_\mu}{\sqrt{g^2 + g'^2}}$$

$$M_{Z^0} = \sqrt{g^2 + g'^2}\, v/2 = M_W \sqrt{1 + g'^2/g^2}$$

$\boxed{A_\mu \text{ remains massless}}$

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -\zeta_e \frac{(v+\eta)}{\sqrt{2}}(\bar{e}_R e_L + \bar{e}_L e_R) \\ &= -\frac{\zeta_e v}{\sqrt{2}}\bar{e}e - \frac{\zeta_e \eta}{\sqrt{2}}\bar{e}e\end{aligned}$$

electron acquires $m_e = \zeta_e v/\sqrt{2}$

$\boxed{\text{Higgs-boson coupling to electrons: } m_e/v \quad (\propto \text{mass})}$

Desired particle content ... plus a Higgs scalar

Values of couplings, electroweak scale v?

Then analyze interactions ...

The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass,

but partial-wave unitarity defines tipping point

Gedanken experiment: high-energy scattering of

$$W_L^+ W_L^- \quad Z_L^0 Z_L^0/\sqrt{2} \quad HH/\sqrt{2} \quad HZ_L^0$$

L: longitudinal, $1/\sqrt{2}$ for identical particles

The importance of the 1-TeV scale . . .

In HE limit, s-wave amplitudes $\propto G_F M_H^2$

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix}$$

Require that largest eigenvalue respect partial-wave unitarity condition $|a_0| \le 1$

$$\Longrightarrow \quad M_H \le \left(\frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} = 1 \text{ TeV}$$

condition for perturbative unitarity

The importance of the 1-TeV scale . . .

If the bound is respected

- weak interactions remain weak at all energies
- perturbation theory is everywhere reliable

If the bound is violated

- perturbation theory breaks down
- weak interactions among $W^{\pm}$, Z, H
  become strong on 1-TeV scale

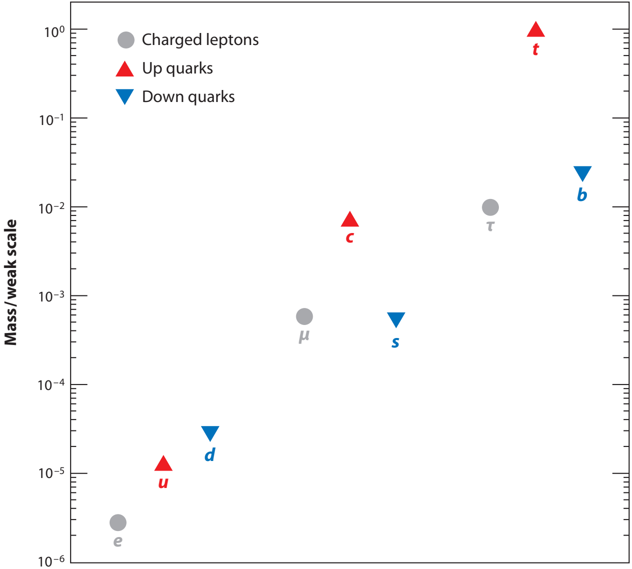
New phenomena are to be found in the EW interactions at energies not much larger than 1 TeV

Electroweak Questions for the LHC

- What hides electroweak symmetry: a Higgs boson, or new strong dynamics?
- If a Higgs boson: one or several?
- Elementary or composite?
- Is the Higgs boson indeed light, as anticipated by the global fits to EW precision measurements?
- Does H only give masses to $W^{\pm}$ and Z^0, or also to fermions? (Infer $t\bar{t}H$ from production)
- Are the branching fractions for $f\bar{f}$ decays in accord with the standard model?

If all this: what sets the fermion masses and mixings?

Fermion Mass Generation



Search for the Standard-Model Higgs Boson

$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

$\propto M_H$ in the limit of large Higgs mass; $\propto \beta^3$ for scalar

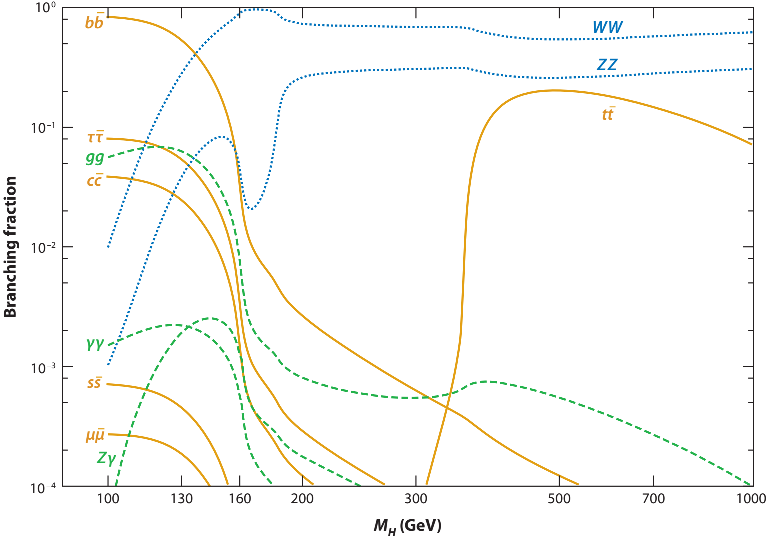
$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^3}{32\pi\sqrt{2}}(1-x)^{1/2}(4-4x+3x^2) \quad x \equiv 4M_W^2/M_H^2$$

$$\Gamma(H \to Z^0Z^0) = \frac{G_F M_H^3}{64\pi\sqrt{2}}(1-x')^{1/2}(4-4x'+3x'^2) \quad x' \equiv 4M_Z^2/M_H^2$$

asymptotically $\propto M_H^3$ and $\frac{1}{2}M_H^3$, respectively

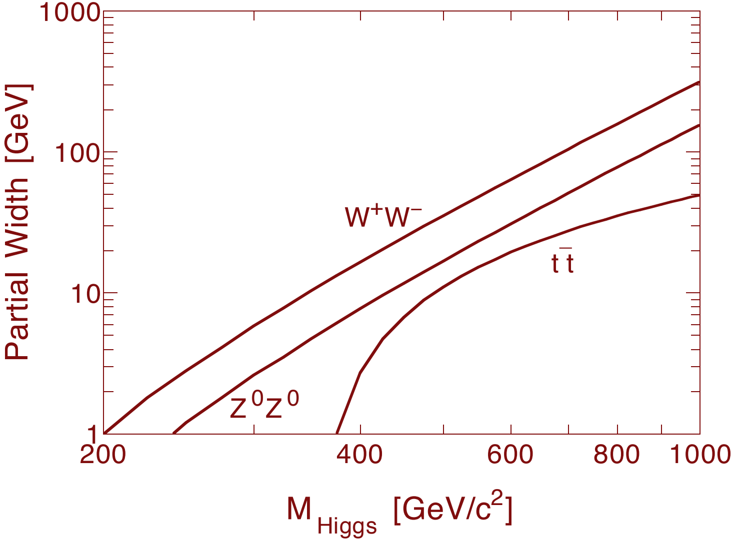
$2x^2$ and $2x'^2$ terms $\Leftrightarrow$ decays into transverse gauge bosons
Dominant decays for large M_H: pairs of longitudinal weak bosons

SM Higgs Boson Branching Fractions



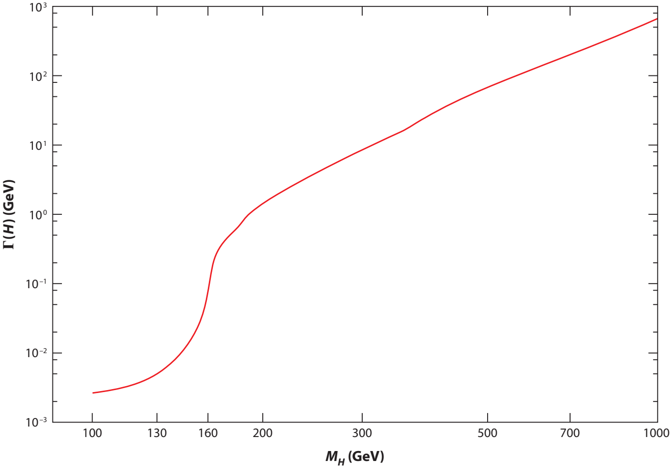
Djouadi, hep-ph/0503172

Dominant decays at high mass



For $M_H \to 1$ TeV, Higgs boson is *ephemeral:* $\Gamma_H \to M_H$.

Total width of the standard-model Higgs boson



Below W^+W^- threshold, $\Gamma_H \lesssim 1$ GeV

Far above W^+W^- threshold, $\Gamma_H \propto M_H^3$

A few words on Higgs production . . .

$e^+e^- \to H$: hopelessly small
$\mu^+\mu^- \to H$: scaled by $(m_\mu/m_e)^2 \approx 40\,000$
$e^+e^- \to HZ$: prime channel

Hadron colliders:
$gg \to H \to b\bar{b}$: background ?!
$gg \to H \to \tau\tau, \gamma\gamma$: rate ?!

$gg \to H \to W^+W^-$: best Tevatron sensitivity now
$\bar{p}p \to H(W, Z)$: prime Tevatron channel for light Higgs

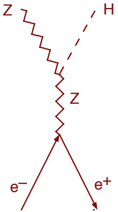
At the LHC:
Many channels accessible, search sensitive up to 1 TeV

Higgs search in e^+e^- collisions

$\sigma(e^+e^- \to H \to \text{all})$ is *minute*, $\propto m_e^2$

Even narrowness of low-mass H is not enough to make it visible ... Sets aside a traditional strength of e^+e^- machines—*pole physics*

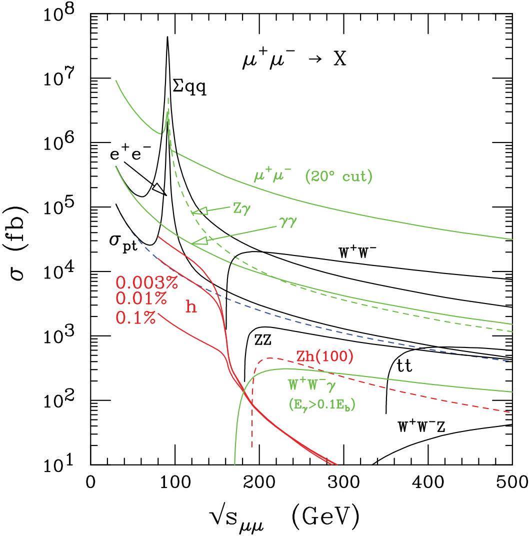
Most promising:
associated production $e^+e^- \to HZ$
(has no small couplings)



$$\boxed{\sigma = \frac{\pi\alpha^2}{24\sqrt{s}} \frac{K(K^2 + 3M_Z^2)[1 + (1 - 4x_W)^2]}{(s - M_Z^2)^2 \quad x_W^2(1 - x_W)^2}}$$

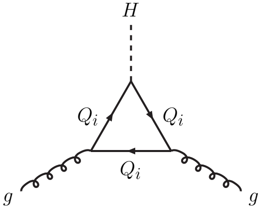
K: c.m. momentum of H $\qquad$ $x_W \equiv \sin^2\theta_W$

$\ell^+\ell^- \to X \ldots$

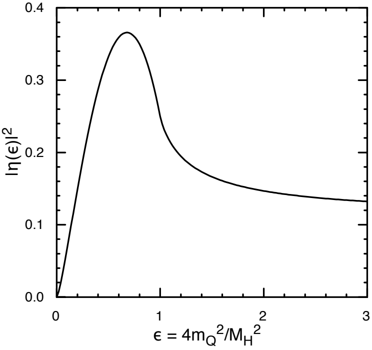


$$\sigma(e^+e^- \to H) = (m_e/m_\mu)^2 \sigma(\mu^+\mu^- \to H) \approx \sigma(\mu^+\mu^- \to H)/40\,000$$

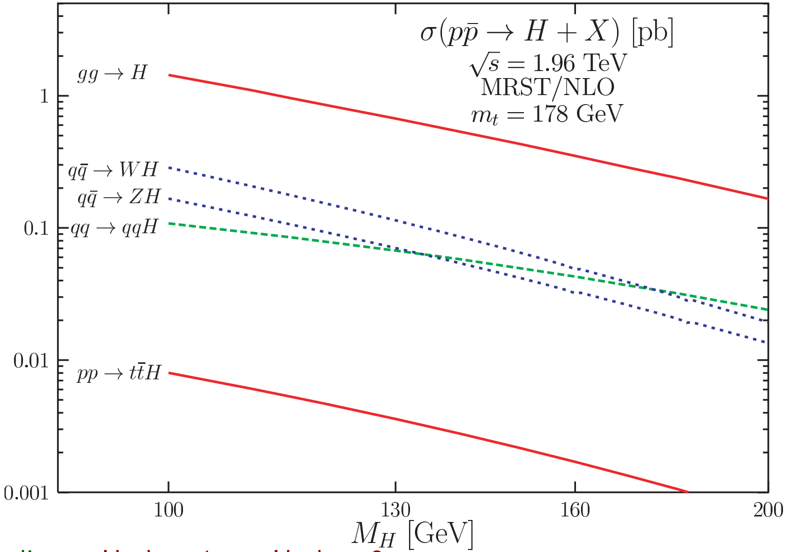
H couples to gluons through quark loops



Only heavy quarks matter: heavy 4th generation ??

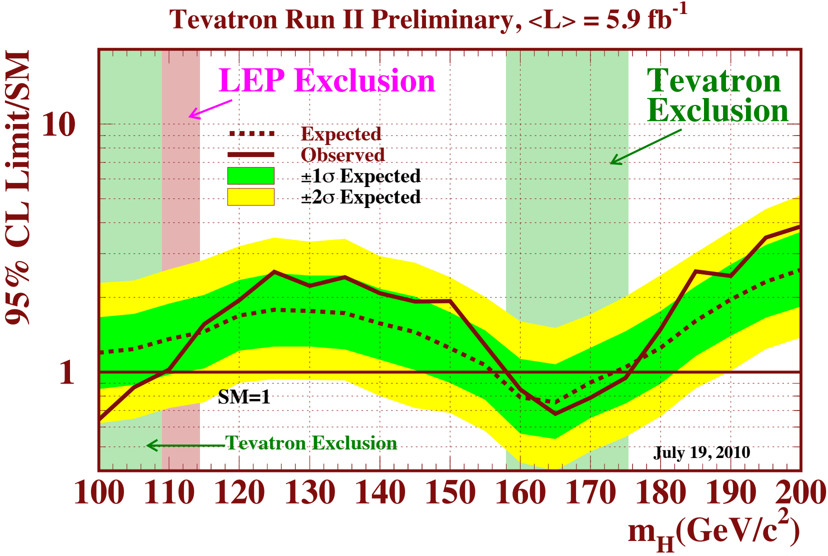


Higgs-boson production at the Tevatron



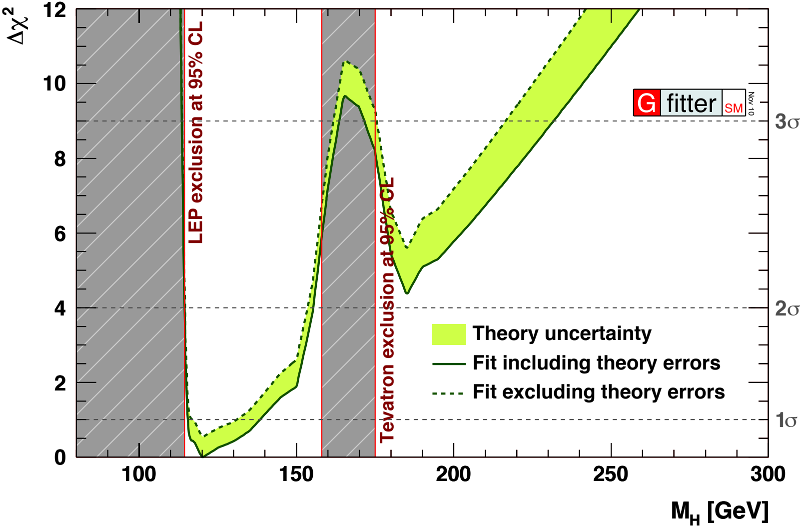
Djouadi Update 1 Update 2

Current Tevatron Sensitivity

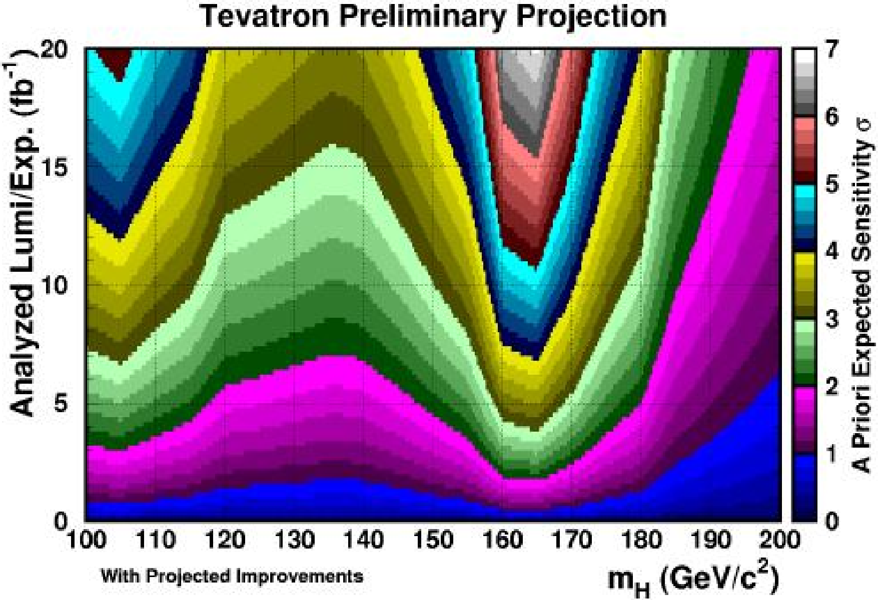


combining experiments, channels: Summer 2010

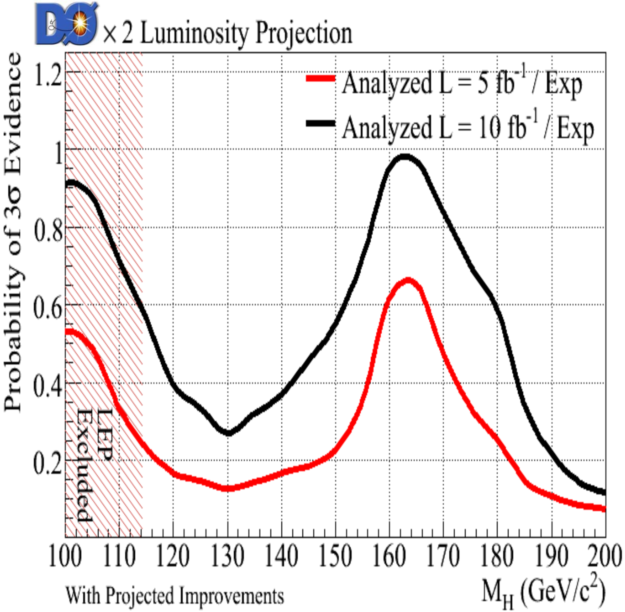
Electroweak theory projection
Global fit + exclusions



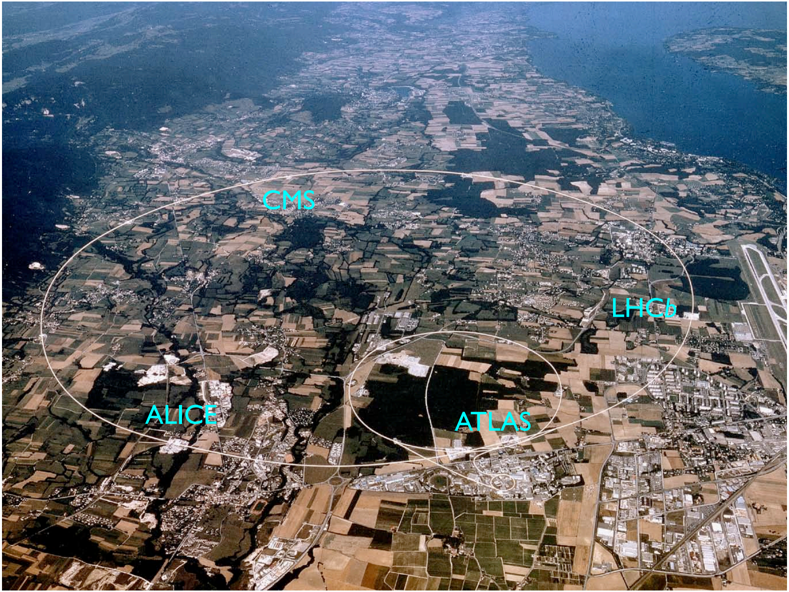
Tevatron prospects . . . $2\times$ CDF, June 2010



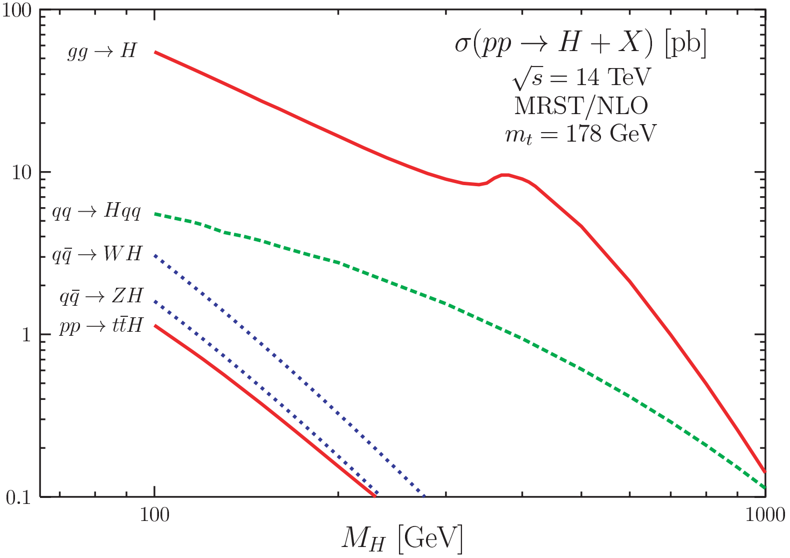
Tevatron prospects . . . Denisov, La Thuile 2010



Large Hadron Collider: pp at $\sqrt{s} \to 14$ TeV



LHC cross sections . . .



Djouadi

Higgs 2011/2012

What do we know today ?

- Theory: $m_H < 1$ TeV
- Present experimental exclusion: $m_H > 114.4$ GeV (LEP),
  $158 < m_H < 175$ GeV (Tevatron)
- Favoured region (electroweak data → consistency of Standard Model):
  $m_H < 158$ GeV

→ 114.4-158 GeV is the “hottest” region (although higher masses cannot be excluded)

Expected Higgs mass coverage (GeV) at LHC

	Tevatron 10 fb^{-1} (end 2011)	LHC 1 fb^{-1} 7 TeV	LHC 1 fb^{-1} 8 TeV	LHC 2.5 fb^{-1} 8 TeV	LHC 5 fb^{-1} 8 TeV
95% CL exclusion	114-185	123-550	120-570	114-600	≥ 114
3 σ evidence	~115, 150-180	130-450	127-500	123-530	≥ 114
5 σ discovery	---	152-174	150-176	138-220	120-570

LHC means ATLAS and CMS combined
(very preliminary)

January 2011

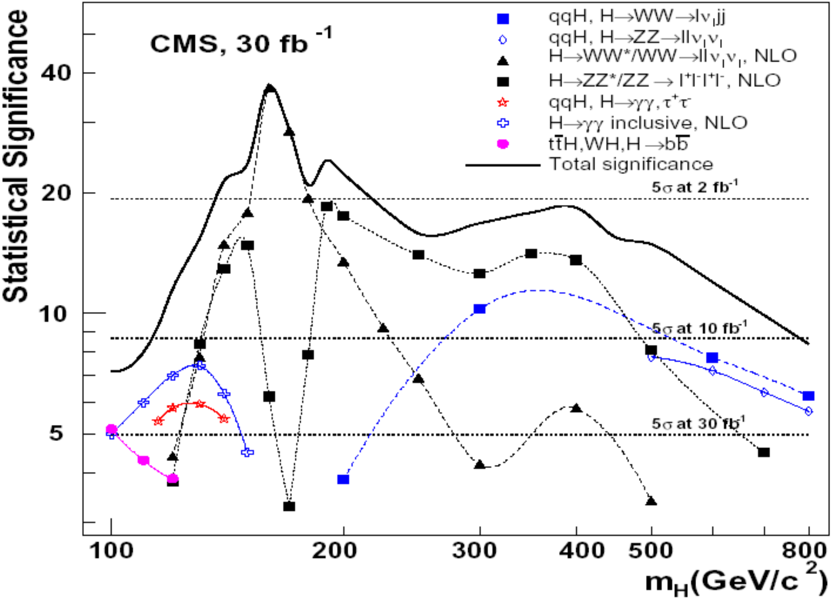
If the Higgs is not there →
LHC needs **~2.5 fb^{-1} for exclusion** down to lowest masses

If the Higgs exists:
- Need **~5 fb^{-1} for 3σ evidence** around $m_H \sim 115$ GeV, but enough sensitivity at higher masses (above ~ 120 GeV) already with 1-3 fb^{-1}
- Discovery (5σ) over full allowed mass region requires ~10 fb^{-1} at 8 TeV

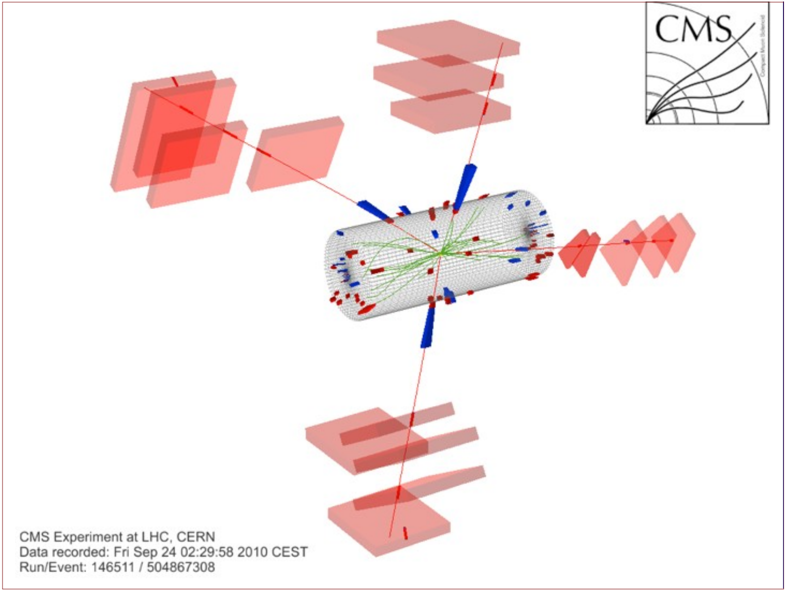
LHC means ATLAS and CMS combined
(very preliminary)

Note on 8 TeV vs 7 TeV:
-- same reach with ~20% less luminosity
-- for same luminosity, extend low-mass reach down by ~ 3 GeV

Example of CMS Significance Projections



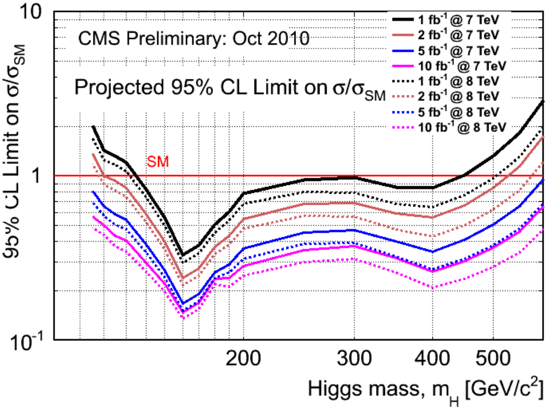
Heavy Higgs Signature: $ZZ \to \mu^+\mu^-\mu^+\mu^-$



LHC Higgs Outlook

- **Combining all modes: search essentially complete with 5-10 fb^{-1}**
  - **Can certainly exclude it at 95%CL throughout the “relevant” region**
  - **Also 3σ effects**

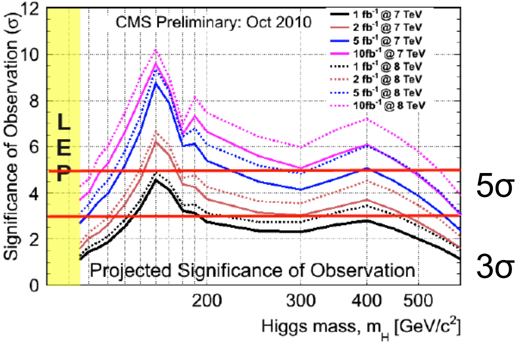
7 TeV		8 TeV	
—	1 fb^{-1}	---	1 fb^{-1}
—	2 fb^{-1}	---	2 fb^{-1}
—	5 fb^{-1}	---	5 fb^{-1}
—	10 fb^{-1}	---	10 fb^{-1}



P. Sphicas, Academic Training CERN 2011

LHC Higgs Outlook

- **Discovery (aka 5σ) bottom line:**
  - **No discovery with 1fb^{-1}. Firm observation with 5 fb^{-1}: in the range 140-230 GeV**
  - **With two experiments: lower end: add ~10 GeV; upper end: ~500 GeV**



P. Sphicas, Academic Training CERN 2011

XVI Escola Jorge Swieca

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

Why Electroweak Symmetry Breaking Matters

PHYSICAL REVIEW D **79,** 096002 (2009)

Gedanken worlds without Higgs fields: QCD-induced electroweak symmetry breaking

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(Received 29 January 2009; published 4 May 2009)

To illuminate how electroweak symmetry breaking shapes the physical world, we investigate toy models in which no Higgs fields or other constructs are introduced to induce spontaneous symmetry breaking. Two models incorporate the standard $\mathrm{SU(3)_c \otimes SU(2)_L \otimes U(1)}_Y$ gauge symmetry and fermion content similar to that of the standard model. The first class—like the standard electroweak theory—contains no bare mass terms, so the spontaneous breaking of chiral symmetry within quantum chromodynamics is the only source of electroweak symmetry breaking. The second class adds bare fermion masses sufficiently small that QCD remains the dominant source of electroweak symmetry breaking and the model can serve as a well-behaved low-energy effective field theory to energies somewhat above the hadronic scale. A third class of models is based on the left-right-symmetric $\mathrm{SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)}$ gauge group. In a fourth class of models, built on $\mathrm{SU(4)_{PS} \otimes SU(2)_L \otimes SU(2)_R}$ gauge symmetry, the lepton number is treated as a fourth color and the color gauge group is enlarged to the $\mathrm{SU(4)_{PS}}$ of Pati and Salam (PS). Many interesting characteristics of the models stem from the fact that the effective strength of the weak interactions is much closer to that of the residual strong interactions than in the real world. The Higgs-free models not only provide informative contrasts to the real world, but also lead us to consider intriguing issues in the application of field theory to the real world.

DOI: 10.1103/PhysRevD.79.096002 PACS numbers: 11.15.−q, 12.10.−g, 12.60.−i

Challenge: Understanding the Everyday World

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!
$\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$

Modified Standard Model: No Higgs Sector: $\overline{\mathrm{SM}}_1$

$\mathbf{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ with massless u, d, e, ν

(treat $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ as perturbation)

Nucleon mass little changed:

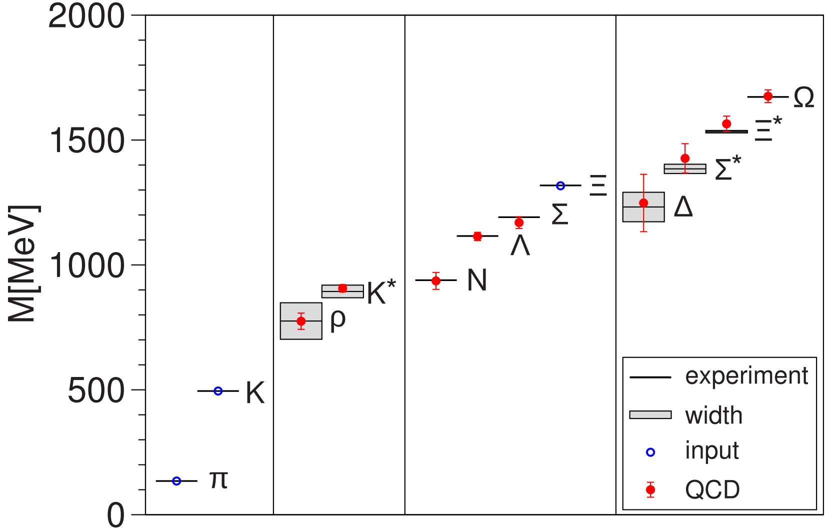
$$M_p = C \cdot \Lambda_{\mathrm{QCD}} + \dots$$

$$3\,\frac{m_u + m_d}{2} = (7.5 \text{ to } 15) \text{ MeV}$$

Small contribution from virtual strange quarks

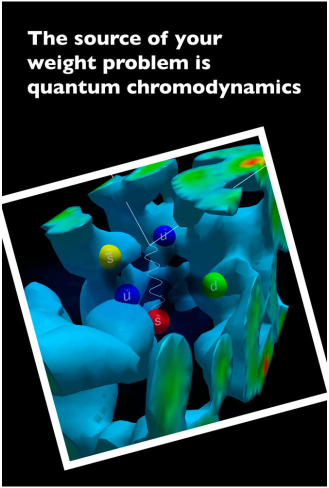
M_N decreases by $< 10\%$ in chiral limit: $939 \rightsquigarrow 870$ MeV

Hadron Masses from Lattice QCD: $M = E_0/c^2$



BMW, *Science* **322,** 1224 (2008)

QCD accounts for (most) visible mass in Universe



(*not* the Higgs boson)

Modified Standard Model: No Higgs Sector: $\overline{\mathrm{SM}}_1$

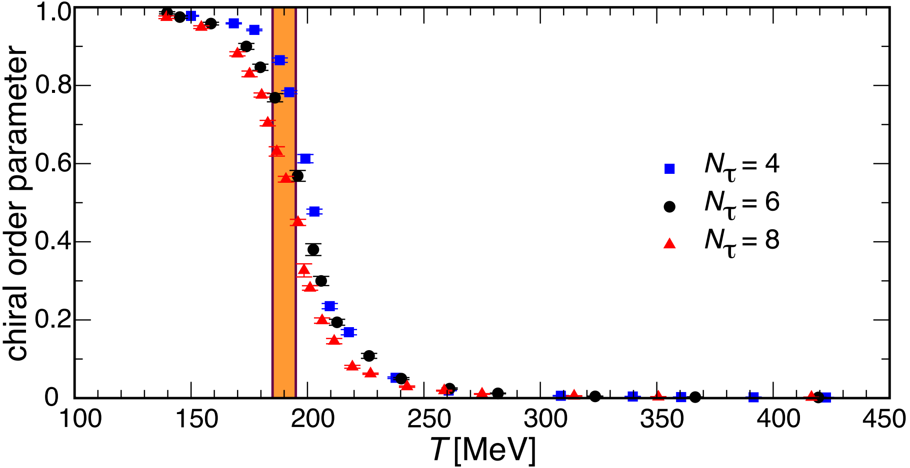
QCD has exact $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ chiral symmetry.

At an energy scale $\sim \Lambda_{\mathrm{QCD}}$, strong interactions become strong, fermion condensates $\langle \bar{q}q \rangle$ appear, and

$$\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R} \to \mathrm{SU(2)_V}$$

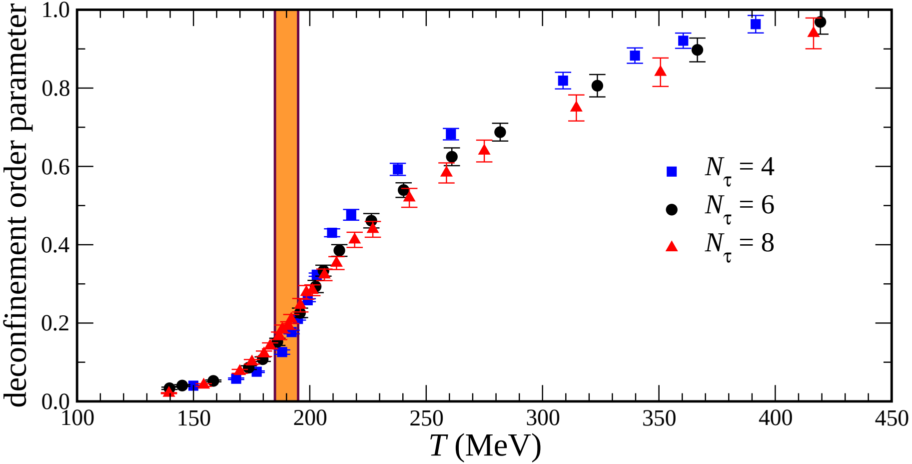
$\leadsto$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Chiral Symmetry Breaking on the Lattice



Weise lecture for review and lattice QCD references

Deconfinement on the Lattice



A. Polyakov, *Phys. Lett.* **B72,** 477 (1978)

Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q}q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

$$1 = \tfrac{1}{2}(1 + \gamma_5) + \tfrac{1}{2}(1 - \gamma_5)$$

$$\mathrm{Q}_{\mathrm{L}}^{a} = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_{\mathrm{L}} \qquad u_{\mathrm{R}}^{a} \quad d_{\mathrm{R}}^{a}$$

$$(\mathrm{SU}(3)_{\mathrm{c}}, \mathrm{SU}(2)_{\mathrm{L}})_{Y}\colon\ (\mathbf{3}, \mathbf{2})_{1/3} \qquad (\mathbf{3}, \mathbf{1})_{4/3} \quad (\mathbf{3}, \mathbf{1})_{-2/3}$$

transforms as $\mathrm{SU}(2)_{\mathrm{L}}$ doublet with $|Y| = 1$

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Broken generators: 3 axial currents; couplings to π: $\bar{f}_\pi$

Turn on $SU(2)_L \otimes U(1)_Y$*:*

Weak bosons couple to axial currents, acquire mass $\sim g\bar{f}_\pi$

$$g \approx 0.65,\ g' \approx 0.34,\ f_\pi = 92.4\ \text{MeV} \rightsquigarrow \bar{f}_\pi \approx 87\ \text{MeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{\bar{f}_\pi^2}{4} \qquad (w_1, w_2, w_3, \mathcal{A})$$

same structure as standard EW theory

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned}\overline{M}_W^2 &= g^2 \bar{f}_\pi^2/4 \\ \overline{M}_Z^2 &= (g^2 + g'^2)\bar{f}_\pi^2/4 \\ \overline{M}_A^2 &= 0\end{aligned}$$

$$\overline{M}_Z^2/\overline{M}_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

NGBs become longitudinal components of weak bosons.

$$\boxed{\overline{M}_W \approx 28 \text{ MeV} \qquad \overline{M}_Z \approx 32 \text{ MeV}}$$

$$(M_W \approx 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV})$$

Electroweak scale

EW theory: *choose* $v = (G_F\sqrt{2})^{-1/2} \approx 246$ GeV

$\overline{\text{SM}}$: *predict*

$$\overline{G}_F = 1/(\bar{f}_\pi^2\sqrt{2}) \approx 93.25\ \text{GeV}^{-2} \approx 8 \times 10^6\ G_F$$

Cross sections, decay rates $\times(\overline{G}_F/G_F)^2 \approx 6.4 \times 10^{13}$

$$\text{Real world: } \sigma(\nu_e n \to e^- p) \approx 10^{-38}\ \text{cm}^{-2}$$

$$\rightsquigarrow \overline{\text{SM}}\text{: } \bar{\sigma}(\nu_e n \to e^- p) \approx \text{ few mb}$$

$\boxed{\text{Weak interaction strength} \sim \text{residual strong interactions}}$

$\overline{\mathrm{SM}}_1$: Hadron Spectrum

Pions absent (became longitudinal $W^{\pm}$, Z^0)

ρ, ω, a_1 "as usual," but

$$\rho^0 \to W^+W^-$$
$$\rho^+ \to W^+Z$$
$$\omega \to W^+W^-Z$$

$M_\Delta > M_N; \quad \Delta \to N(W^{\pm}, Z, \gamma)$

Nucleon mass little changed: look in detail

Nucleon masses . . .

"Obvious" that proton should outweigh neutron

. . . but false in real world: $M_n - M_p \approx 1.293$ MeV

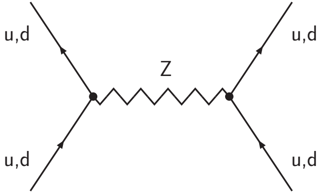
Real-world contributions,

$$\begin{aligned} M_n - M_p &= \cancel{(m_d - m_u)} - \tfrac{1}{3}\left(\delta m_q + \delta M_{\mathrm{C}} + \delta M_{\mathrm{M}}\right) \\ &\leadsto -1.7 \text{ MeV} \end{aligned}$$

. . . but weak contributions enter.

Weak contributions are not negligible

$$\overline{M}_n - \overline{M}_p\big|_{\text{weak}} \propto dd - uu$$



$$\overline{M}_n - \overline{M}_p\big|_{\text{weak}} = \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{3} x_{\text{W}}(1 - 2x_{\text{W}}) \approx \frac{\overline{G}_{\text{F}}\Lambda_{\text{h}}^3\sqrt{2}}{24}$$

$$= \frac{\Lambda_{\text{h}}^3}{3\bar{f}_\pi^2} x_{\text{W}}(1 - 2x_{\text{W}}) \approx \frac{\Lambda_{\text{h}}^3}{24\bar{f}_\pi^2} > 0$$

$x_{\text{W}} = sin^2\theta_{\text{W}} \approx \frac{1}{4}$

perhaps a few MeV?

Consequences for β decay

Scale decay rate $\Gamma \sim \overline{G}_F^2 |\overline{\Delta M}|^5 / 192\pi^3$ (rapid!)

$$\bar{\tau}_\mu \longrightarrow 10^{-19}\ \text{s}$$

$$n \longrightarrow p e^- \bar{\nu}_e \text{ or } p \longrightarrow n e^+ \nu_e$$

Example: $\left|\overline{M}_n - \overline{M}_p\right| = M_n - M_p \rightsquigarrow \bar{\tau}_N \approx 14$ ps

$\boxed{\text{No Hydrogen Atom?}}$

Neutron could be lightest nucleus

Strong coupling in $\overline{\text{SM}}$

In SM, Higgs boson regulates high-energy behavior

Gedanken experiment: scattering of

$$W_L^+ W_L^- \quad \frac{Z_L^0 Z_L^0}{\sqrt{2}} \quad \frac{HH}{\sqrt{2}} \quad HZ_L^0$$

In high-energy limit, s-wave amplitudes

$$\lim_{s \gg M_H^2} (a_0) \to \frac{-G_F M_H^2}{4\pi\sqrt{2}} \cdot \begin{bmatrix} 1 & 1/\sqrt{8} & 1/\sqrt{8} & 0 \\ 1/\sqrt{8} & 3/4 & 1/4 & 0 \\ 1/\sqrt{8} & 1/4 & 3/4 & 0 \\ 0 & 0 & 0 & 1/2 \end{bmatrix} .$$

Strong coupling in $\overline{\text{SM}}$

In *standard model,* $|a_0| \leq 1$ yields

$$M_H \leq \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 4v\sqrt{\pi/3} = 1\ \text{TeV}$$

In $\overline{\text{SM}}_1$ *Gedanken* world,

$$\overline{M}_H \leq \left(\frac{8\pi\sqrt{2}}{3\overline{G}_F}\right)^{1/2} = 4\bar{f}_\pi\sqrt{\pi/3} \approx 350\ \text{MeV}$$

violated because no Higgs boson $\rightsquigarrow$ strong scattering

Strong coupling in $\overline{\text{SM}}$

SM with (very) heavy Higgs boson:

s-wave W^+W^-, Z^0Z^0 scattering as $s \gg M_W^2, M_Z^2$:

$$a_0 = \frac{s}{32\pi v^2}\begin{bmatrix} 1 & \sqrt{2} \\ \sqrt{2} & 0 \end{bmatrix}$$

Largest eigenvalue: $a_0^{\text{max}} = s/16\pi v^2$

$$|a_0| \le 1 \Rightarrow \sqrt{s^\star} = 4\sqrt{\pi}v \approx 1.74 \text{ TeV}$$

$$\boxed{\overline{\text{SM}}\text{: } \sqrt{s^\star} = 4\sqrt{\pi}\bar{f}_\pi \approx 620 \text{ MeV}}$$

$\overline{\text{SM}}$ becomes strongly coupled on the hadronic scale

Strong coupling in $\overline{\text{SM}}$

As in standard model . . .

$I = 0$, $J = 0$ and $I = 1$, $J = 1$: attractive

$I = 2$, $J = 0$: repulsive

As partial-wave amplitudes approach bounds,
WW, WZ, ZZ resonances form,
multiple production of W and Z

in emulation of $\pi\pi$ scattering approaching 1 GeV

Detailed projections depend on unitarization protocol

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

No integrity of matter, no stable structures

Summary

Massless fermion pathologies . . .

Vacuum readily breaks down to e^+e^- plasma

. . . persists with GUT-induced tiny masses

"hard" fermion masses: explicit $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ breaking

NGBs $\longrightarrow$ pNGBs

$$\mathrm{SM}m\text{: } a_J(f\bar{f} \to W_L^+ W_L^-) \propto G_\mathrm{F} m_f E_\mathrm{cm}$$

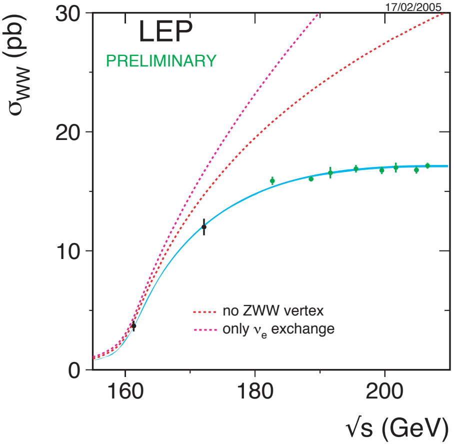
saturate p.w. unitarity at

$$\sqrt{s_f} \simeq \frac{4\pi\sqrt{2}}{\sqrt{3\eta_f}\, G_\mathrm{F} m_f} = \frac{8\pi v^2}{\sqrt{3\eta_f}\, m_f}$$

$\eta_f = 1(N_\mathrm{c})$ for leptons (quarks)

"Hard" electron mass: $\sqrt{s_e} \approx 1.7 \times 10^9$ GeV ...

Gauge cancellation need not imply renormalizable theory



"Hard" top mass: $\sqrt{s_t} \approx 3$ TeV

Add explicit fermion masses to $\overline{\text{SM}}$: $\rightsquigarrow$ $\overline{\text{SM}}m$

$a_J(f\bar{f} \to W_L^+ W_L^-)$ unitarity respected up to

$$\sqrt{s^\star} = 4\sqrt{\pi n_g}\bar{f}_\pi \approx 620\sqrt{n_g}\ \text{MeV}$$

(condition from WW scattering)

$$\rightsquigarrow m_f \lesssim \frac{2\sqrt{\pi n_g}\bar{f}_\pi}{\sqrt{3\eta_f}} \approx \begin{cases} 126\,\sqrt{n_g}\ \text{MeV (leptons)} \\ 73\,\sqrt{n_g}\ \text{MeV (quarks)} \end{cases}$$

would accommodate real-world e, u, d masses

In summary . . .

- $\overline{\mathsf{SM}}$: QCD-induced $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y \to \mathrm{U(1)_{em}}$
- No fermion masses; division of labor?
- No physical pions in $\overline{\mathsf{SM}}_1$
- No quark masses: might proton outweigh neutron?
- Infinitesimal m_e: integrity of matter compromised
- $\overline{\mathsf{SM}}$ exhibits strong W, Z dynamics below 1 GeV
- $\overline{M}_W \approx 30$ MeV in *Gedanken* world
- $\overline{G}_\mathrm{F} \sim 10^7\, G_\mathrm{F}$: accelerates β decay
- Weak, hadronic int. comparable; nuclear forces
- Infinitesimal m_ℓ: vacuum breakdown, e^+e^- plasma
- $\overline{\mathsf{SM}}m$: effective theory through hadronic scale

Outlook

How different a world, without a Higgs mechanism:
preparation for interpreting experimental insights

$\overline{\mathrm{SM}}$, $\overline{\mathrm{SM}}m$: explicit theoretical laboratories
complement to studies that retain Higgs, vary v
(very intricate alternative realities)

Fresh look at the way we have understood the real world
(possibly > 1 source of SSB, "hard" fermion masses)

How might EWSB deviate from the Higgs mechanism?

XVI Escola Jorge Swieca

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

Exploring the New Landscape: *Early Running*

CLNS-131
November 1970
September 1973

(Preliminary Version)

Some Experiments on Multiple Production*

Kenneth G. Wilson
Laboratory of Nuclear Studies, Cornell University,
Ithaca, New York 14850

A program of experiments is described mainly on secondary particle spectra to test scaling hypotheses derived from the multiperipheral model. It is assumed that diffraction dissociation and multiperipheral processes are distinct effects, and the consequences of this for the scaling laws are explained. Feynman's analogy linking multiple production to the statistical mechanical distribution functions of a gas is outlined, and based on this analogy it is suggested that one look for a correlation length in the two particle spectrum of secondaries.

Wilson's Experiments in Multiple Production

- Topological cross sections: multiplicity distributions diffractive + multiperipheral production?
- Feynman scaling: $\rho(k_z/E, k_\perp, E)$ independent of E?
- Factorization: $\rho(k_z/E, k_\perp, E)$ same for $(\pi, p)p$ in proton hemisphere?
- Flat rapidity plateau in central region?
- Double Pomeron exchange?
- Correlation length experiment: $\propto \exp(-|y_1 - y_2|/L)$?
- Factorization test with central trigger (to eliminate diffraction)

Exploring the New Landscape

QCD could be complete, up to ultrahigh energies

. . . *Doesn't mean it must be!*

No structural deficiencies à la electroweak theory

(but strong CP problem remains)

Perhaps . . .

- *new kinds of colored matter beyond quarks gluons (and maybe their superpartners)*
- *quarks might be composite in an unexpected manner*
- $SU(3)_c$ *gauge symmetry might be vestige of a larger, spontaneously broken, color symmetry.*

My speculation . . .

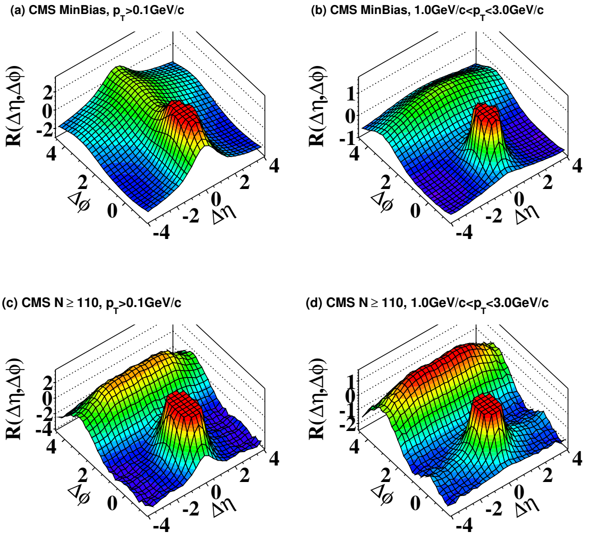
Event structure not a simple extrapolation of Tevatron

LHC's first surprise in this area: not a crack in the foundations, but something perhaps buried within QCD that we have not been clever enough to anticipate.

Some unusual structure in a few percent of events? High-multiplicity hedgehog events? Sporadic event structures? Dozens of small jets or other manifestations of multiple parton collisions?

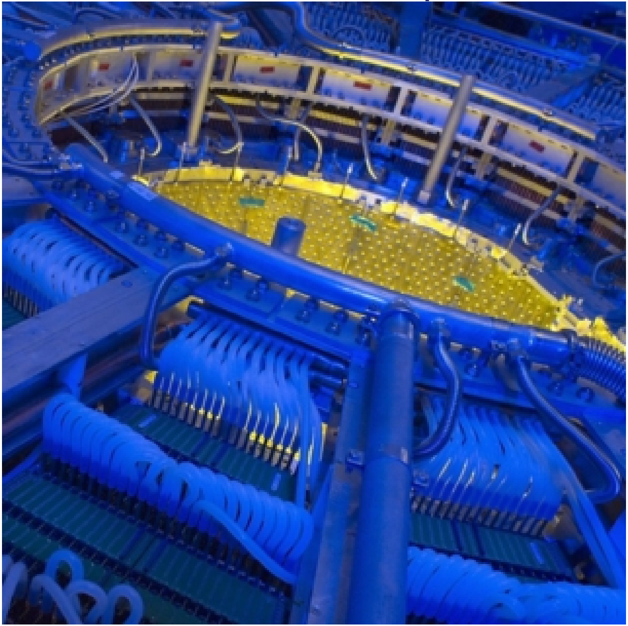
Soft collisions + underlying events
$\rightsquigarrow$ *understanding multiple production, parton showers*

CMS "Ridge" in 7-TeV *pp* Collisions

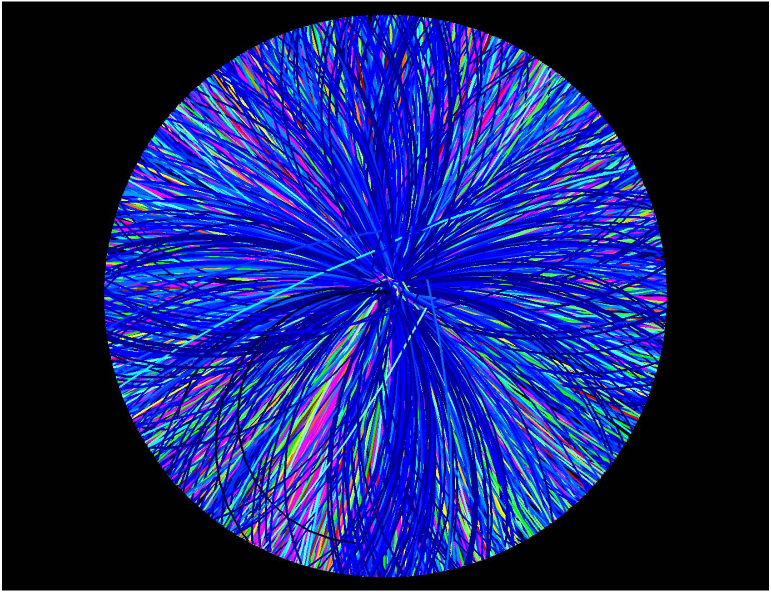


arXiv:1009.4122

Heavy-Ion Collisions: ALICE Experiment



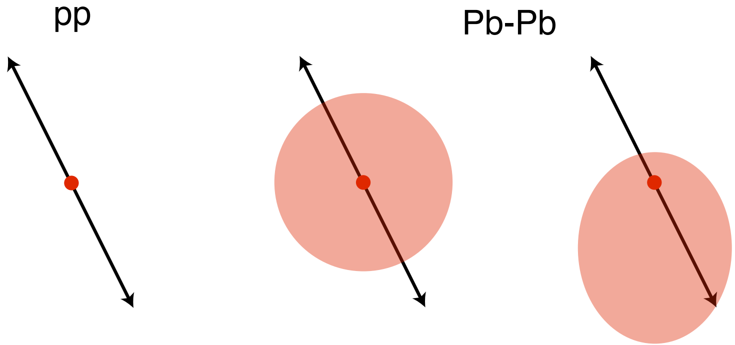
2.76 TeV/A ^{208}Pb ^{208}Pb: ALICE



Heavy-Ion Collisions: Jet Quenching Imagined

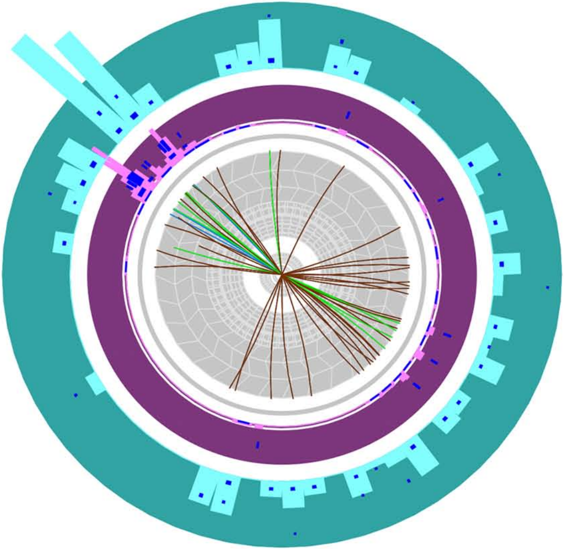
Traversing a hot, dense medium ...

Partons produced in hard scattering lose energy



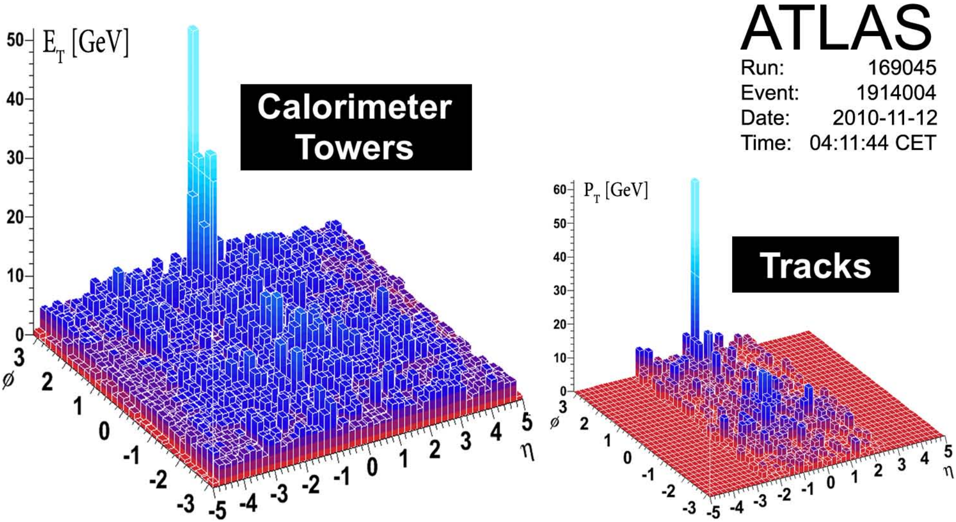
Bjorken, 1982

2.76 TeV/A ^{208}Pb ^{208}Pb: Jet Quenching Observed



ATLAS, arXiv:1011.8182

2.76 TeV/A ^{208}Pb ^{208}Pb: Jet Quenching Observed

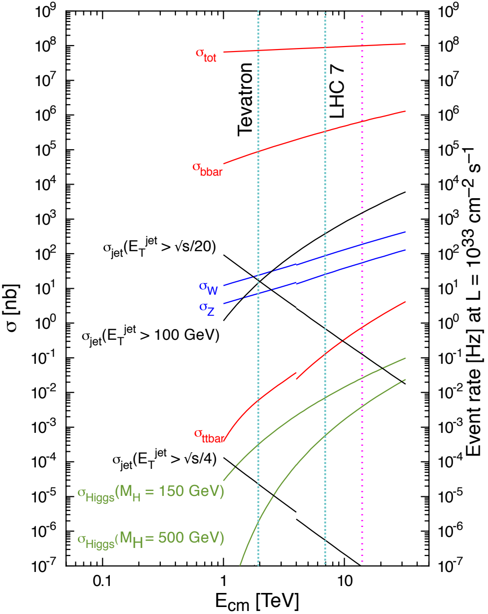


2011 Run of the LHC Begins Soon . . .

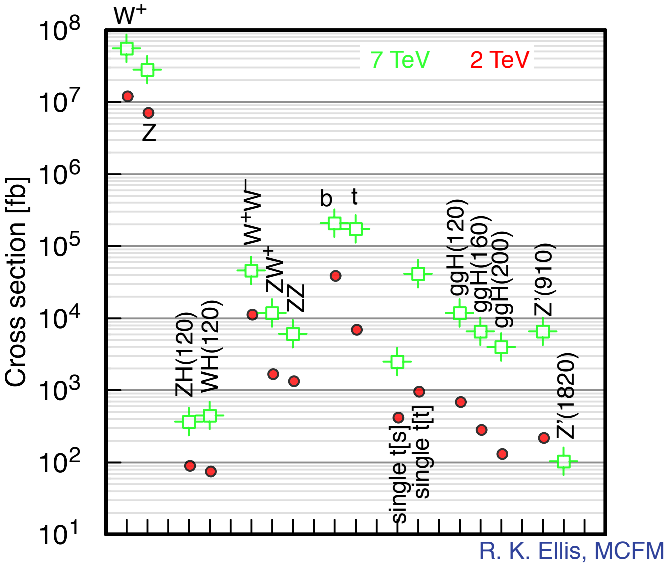
The Large Hadron Collider will run through 2011 at 3.5 TeV per beam, with the energy perhaps rising to 4 TeV/beam in 2012.

- How is the physics potential compromised by running below 14 TeV?
- At what point will the LHC begin to explore virgin territory and surpass the discovery reach of the Tevatron experiments CDF and D0?

Sample event rates in $p^{\pm}p$ collisions



Some Absolute Rates



What Is a Proton?

(For hard scattering) a broad-band, unseparated beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

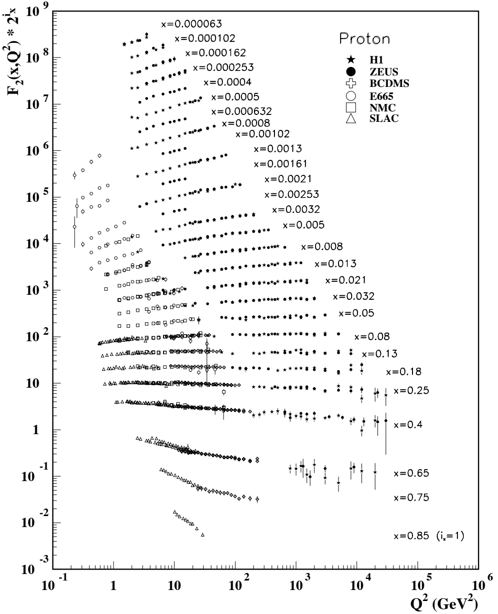
$$f_i^{(a)}(x_a, Q^2),$$

. . . number density of species i with momentum fraction x_a of hadron a seen by probe with resolving power Q^2.

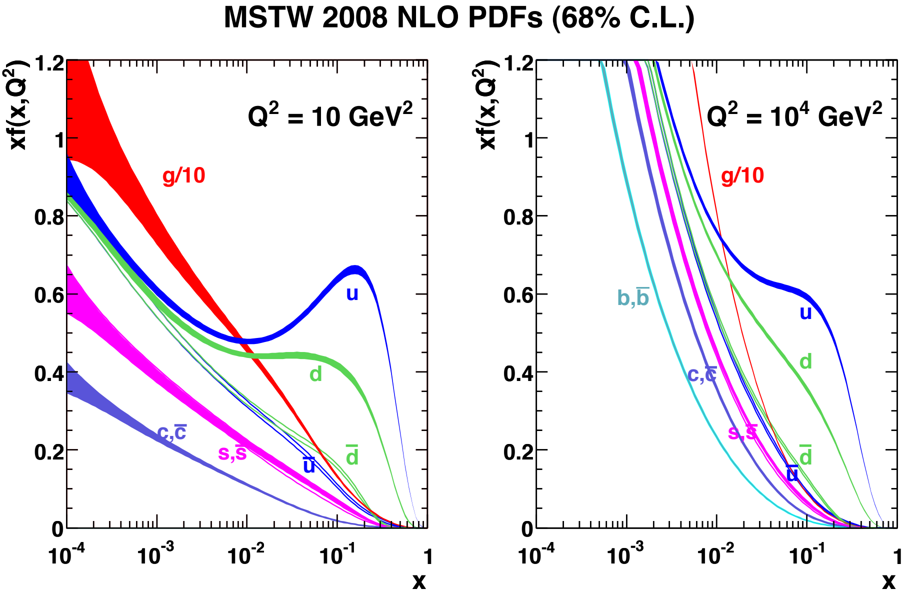
Q^2 evolution given by QCD perturbation theory

$f_i^{(a)}(x_a, Q_0^2)$: nonperturbative

Deeply Inelastic Scattering $\rightsquigarrow f_i^{(a)}(x_a, Q_0^2)$



What Is a Proton?



Hard-scattering cross sections

$$
\begin{aligned}
d\sigma(a+b\to c+X) \;=\; \sum_{ij}\int dx_a dx_b\,\delta(\tau - x_a x_b)\,\cdot \\
f_i^{(a)}(x_a,Q^2) f_j^{(b)}(x_b,Q^2)\, d\hat{\sigma}(i+j\to c+X),
\end{aligned}
$$

$d\hat{\sigma}$: elementary cross section at energy $\sqrt{\hat{s}} = \sqrt{x_a x_b s}$

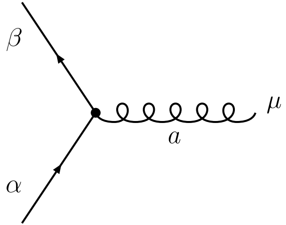
$(\tau = \hat{s}/s)$

Example Leading-Order Calculation

Compute the differential cross section $d\sigma/dt$ for the elementary reaction $ud \to ud$, neglecting quark masses. Show that

$$d\sigma(ud \to ud)/d\hat{t} = \frac{4\pi\alpha_s^2}{9\hat{s}^2} \cdot \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2},$$

where $\hat{s}, \hat{t}, \hat{u}$ are the usual Mandelstam invariants for the parton-parton collision.



$$-\frac{ig}{2}(\lambda^a)_{\alpha\beta}\,\gamma_\mu$$

Preparing to Test QCD in Jet Production

(a) Express the $ud \to ud$ cross section in terms of c.m. angular variables, and note that the angular distribution is reminiscent of that for Rutherford scattering, $d\sigma/d\Omega^* \propto 1/\sin^4(\theta^*/2)$.

(b) In the search for new interactions, the angular distribution for quark-quark scattering, inferred from dijet production in $p^\pm p$ collisions, is a sensitive diagnostic. Show that when re-expressed in terms of the variable $\chi = (1+\cos\theta^*)/(1-\cos\theta^*)$, the angular distribution for ud scattering is $d\sigma/d\chi \propto$ constant.

(c) The rapidity variable, $y = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$, is useful in the study of high-energy collisions because it shifts simply under Lorentz boosts. Show that in the extreme relativistic limit, measuring the jet rapidities in the reaction $p^\pm p \to \text{ jet}_1 + \text{ jet}_2$ leads directly to a determination of the variable χ for parton-parton scattering as $\chi = \exp(y_1 - y_2)$.

Physics Potential versus Energy

arXiv:0908.3660v2 [hep-ph] 8 Sep 2009

LHC Physics Potential *vs.* Energy

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg, $u\bar{d}$, and qq interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes.

arXiv:1101.3201v2 [hep-ph] 1 Feb 2011

LHC Physics Potential *vs.* Energy: Considerations for the 2011 Run

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I quantify the advantage of increasing the beam energy from 3.5 TeV to 4 TeV. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg, $u\bar{d}$, qq, and gq interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes. This note extends the analysis presented in Ref. [1]. Full-size figures are available as pdf files at lutece.fnal.gov/PartonLum11/.

EHLQ, *Rev. Mod. Phys.* **56**, 579 (1984)
Ellis, Stirling, Webber, *QCD & Collider Physics*
MRSW08NLO examples + RKE Lecture 3, SUSSP 2009
Full-page figures: lutece.fnal.gov/PartonLum11

High-energy p: broadband unseparated beam of q, $\bar{q}$, g

Parton Luminosities + Prior Knowledge = Answers

Taking into account $1/\hat{s}$ behavior of hard scattering,

$$\frac{\tau}{\hat{s}}\frac{d\mathcal{L}}{d\tau} \equiv \frac{\tau/\hat{s}}{1+\delta_{ij}} \int_\tau^1 \frac{dx}{x}[f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]$$

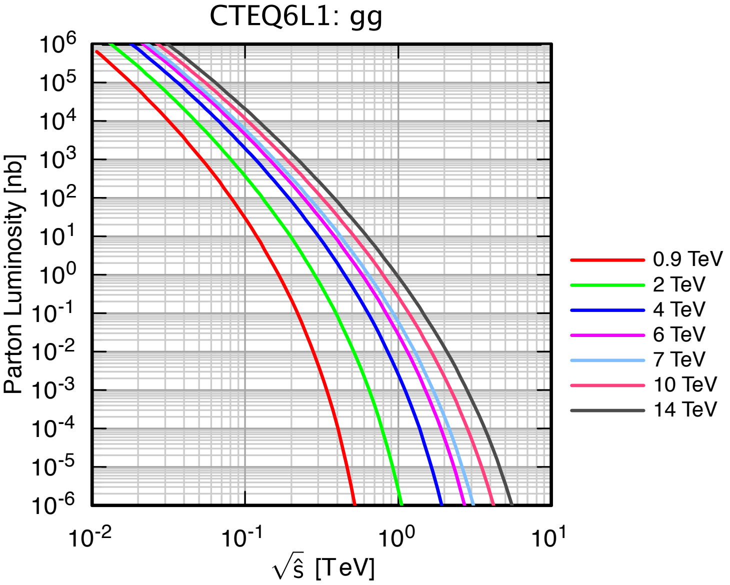
is a convenient measure of parton *ij* luminosity.

$$f_i^{(a)}(x)\text{: pdf;} \quad \tau = \hat{s}/s$$

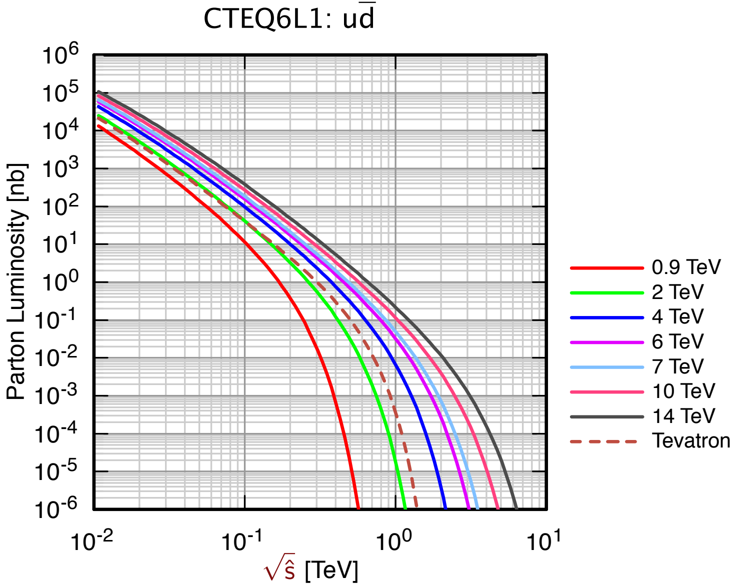
$$\sigma(s) = \sum_{\{ij\}} \int_{\tau_0}^1 \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \cdot [\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

EHLQ §2; *QCD & Collider Physics*, §7.3

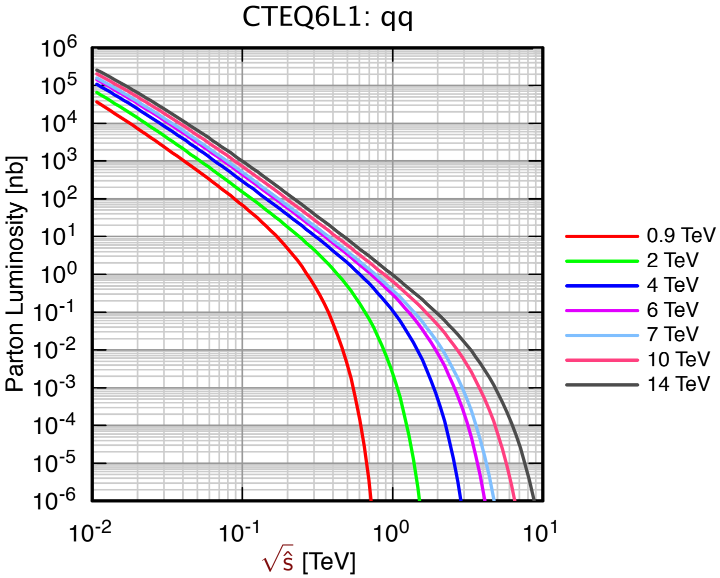
Parton Luminosity



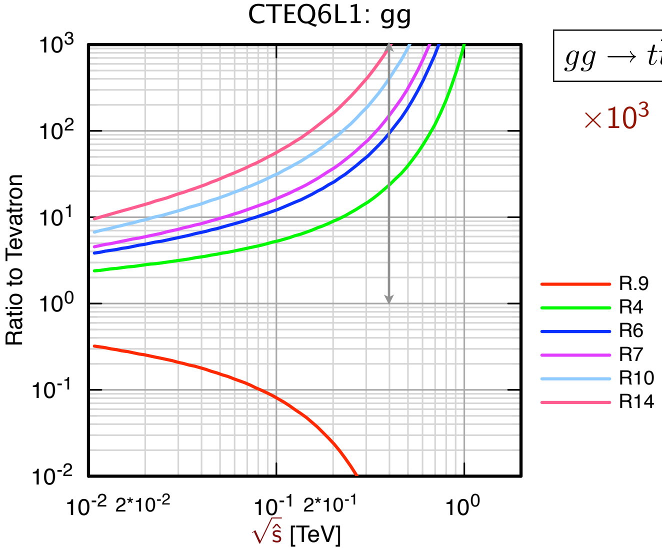
Parton Luminosity



Parton Luminosity (light quarks)



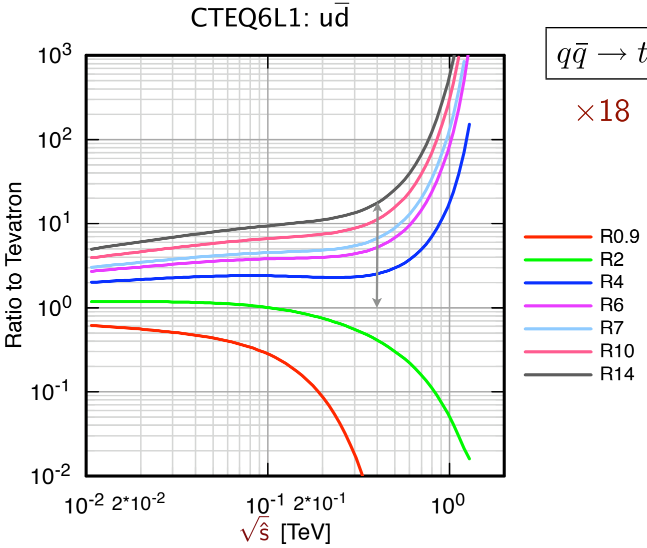
Luminosity Ratios



$\boxed{gg \to t\bar{t}}$

$\times 10^3$

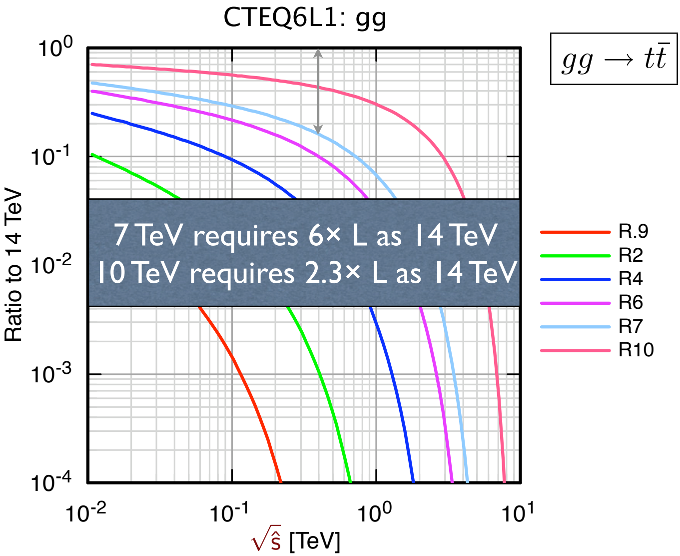
Luminosity Ratios



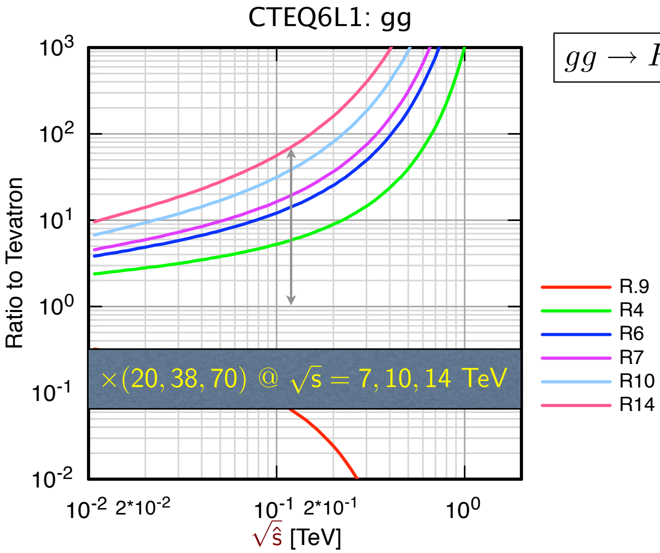
$$\boxed{q\bar{q} \to t\bar{t}}$$

$\times 18$

Luminosity Ratios

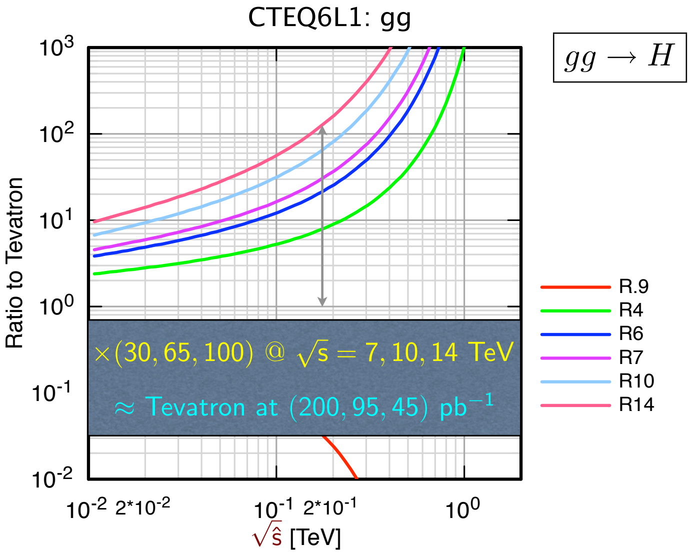


Luminosity Ratios



$$gg \to H$$

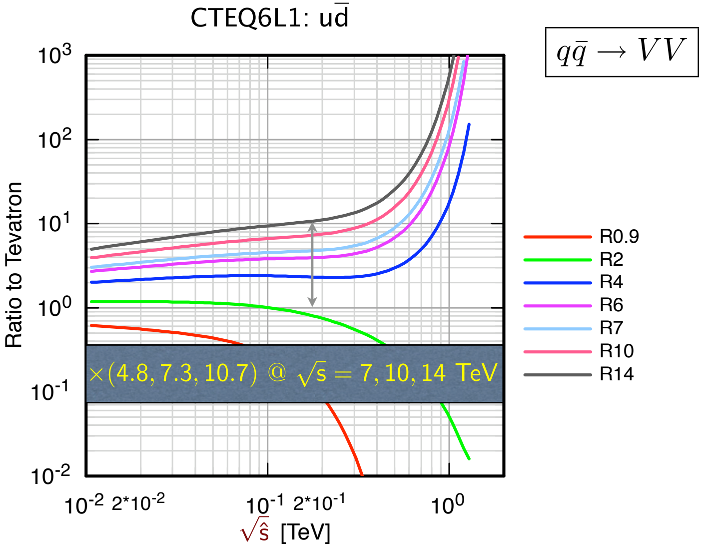
Luminosity Ratios



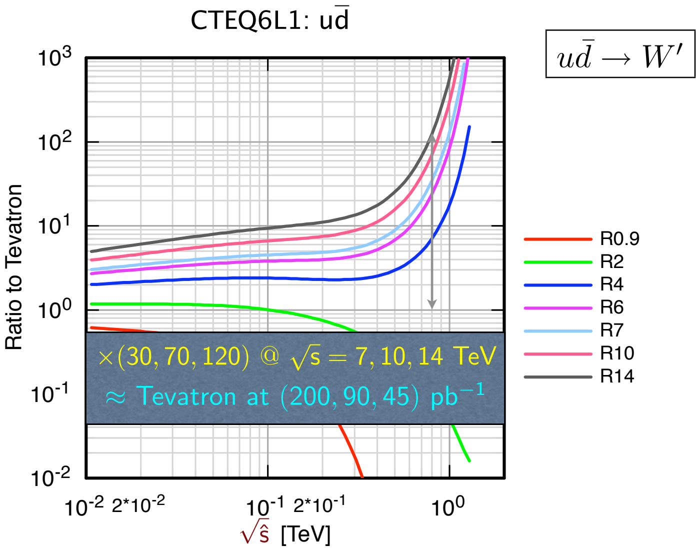
$\times(30, 65, 100)$ @ $\sqrt{s} = 7, 10, 14$ TeV

$\approx$ Tevatron at $(200, 95, 45)$ pb^{-1}

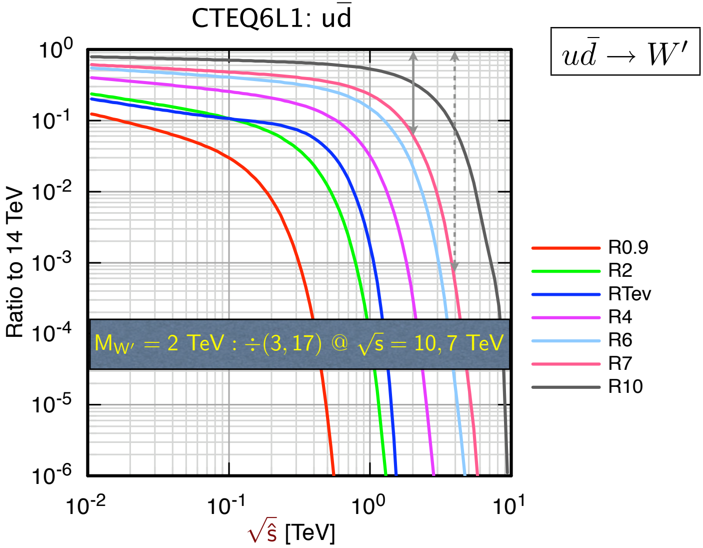
Luminosity Ratios



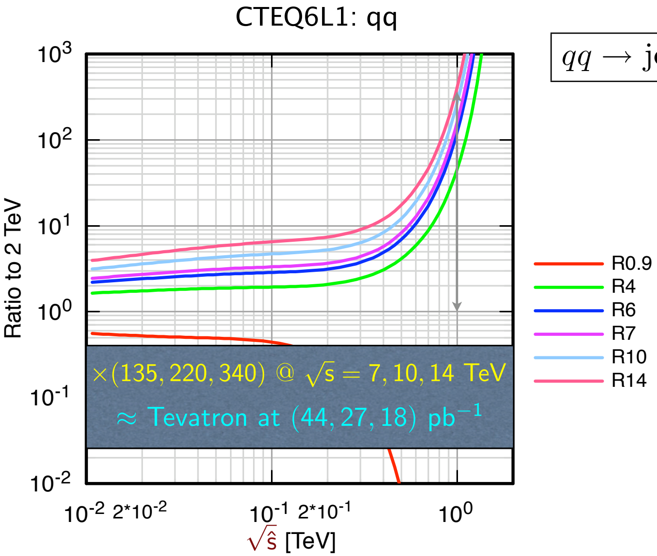
Luminosity Ratios



Luminosity Ratios



Luminosity Ratios

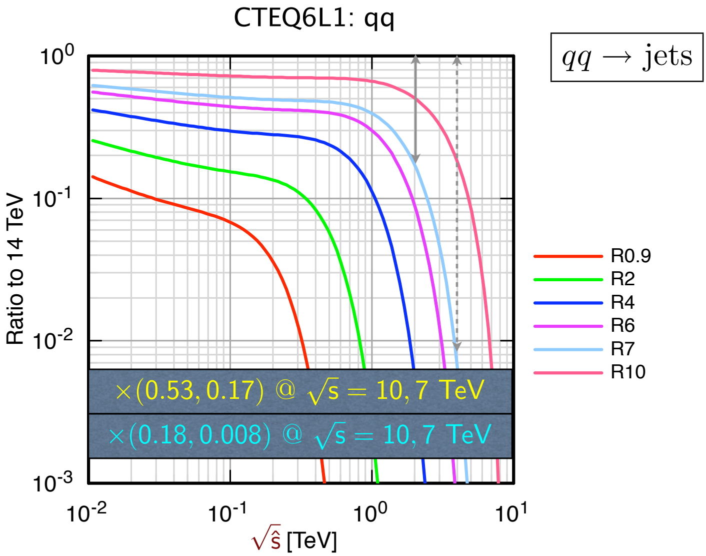


$qq \to \text{jets}$

$\times(135, 220, 340)$ @ $\sqrt{s} = 7, 10, 14$ TeV

$\approx$ Tevatron at $(44, 27, 18)$ pb^{-1}

Luminosity Ratios



Supermodels

New physics possibilities in very early running

Supermodels for early LHC

Christian W. Bauer,[1,2] Zoltan Ligeti,[1,2] Martin Schmaltz,[1,2,3] Jesse Thaler,[1,2] and Devin G. E. Walker[1,2,4]

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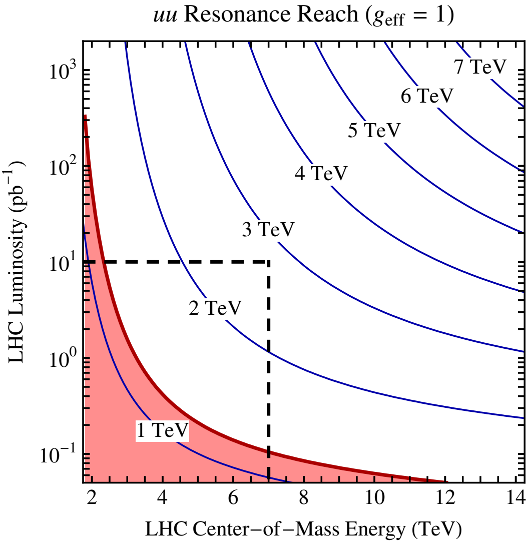
[2] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720*
[3] *Physics Department, Boston University, Boston, MA 02215*
[4] *Center for the Fundamental Laws of Nature, Jefferson Physical Laboratory, Harvard University, Cambridge, MA 02138*

We investigate what new physics signatures the LHC can discover in the 2009–2010 run, beyond the expected sensitivity of the Tevatron data by 2010. We construct "supermodels", for which the LHC sensitivity even with only 10 pb^{-1} is greater than that of the Tevatron with 10 fb^{-1}. The simplest supermodels involve s-channel resonances in the quark-antiquark and especially in the quark-quark channels. We concentrate on easily visible final states with small standard model backgrounds, and find that there are simple searches, besides those for Z' states, which could discover new physics in early LHC data. Many of these are well-suited to test searches for "more conventional" models, often discussed for multi-fb^{-1} data sets.

Rules of the game:

- $\gtrsim$ 10 signal events in 10 pb^{-1} at LHC (25 better)
- No signal in 10 fb^{-1} at Tevatron
- Easily detected, low-background decay channel
- Consistent with existing constraints

Supermodels
Example: strongly coupled *qq* resonance



Supermodels

To observe diquark, require decays beyond qq

An example: color-**6** diquark D + leptodiquark L (!)

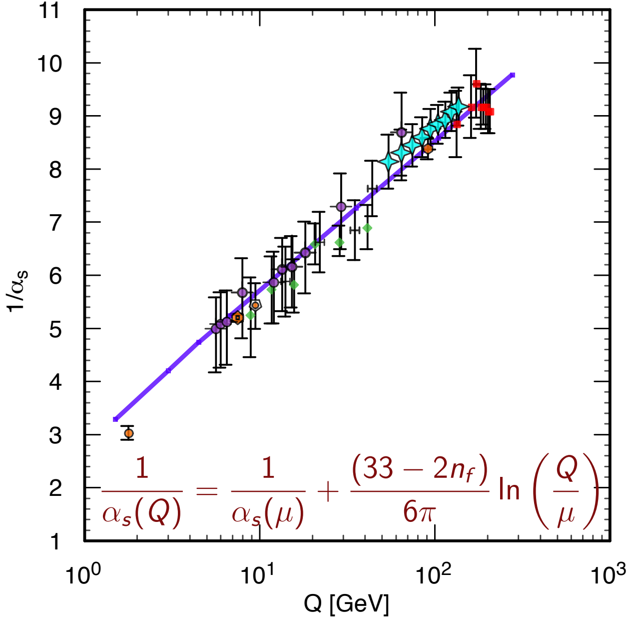
$$
\begin{array}{l}
uu \;\rightarrow\; D \\
\qquad\quad \hookrightarrow \ell^- L \\
\qquad\qquad\quad \hookrightarrow \ell^+ jj
\end{array}
$$

Doesn't respond to any needs, but . . .

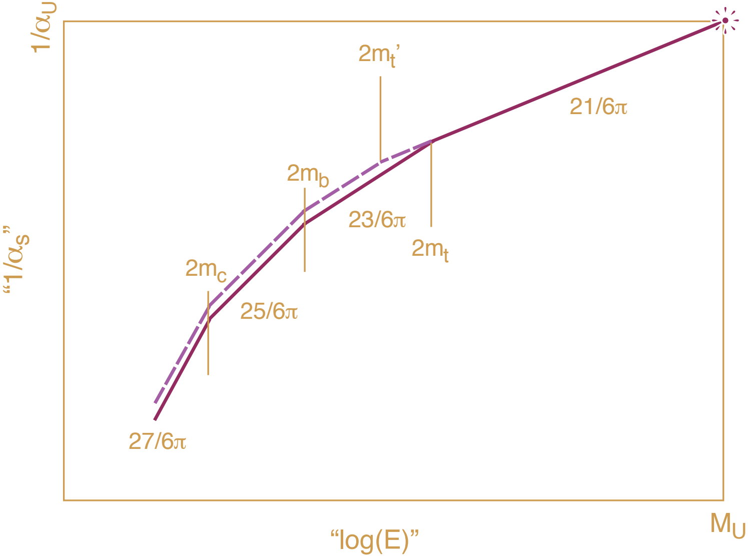
final state familiar from W_{R} searches

$\boxed{\text{Don't assume there is nothing to find at low } \int \mathcal{L}dt}$

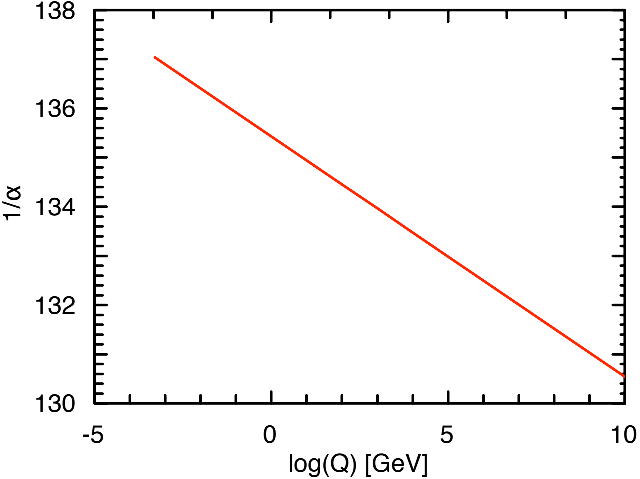
Evolution of $\alpha_s(Q^2)$: Asymptotic Freedom



Evolution of $\alpha_s(Q^2)$: Influence of m_t

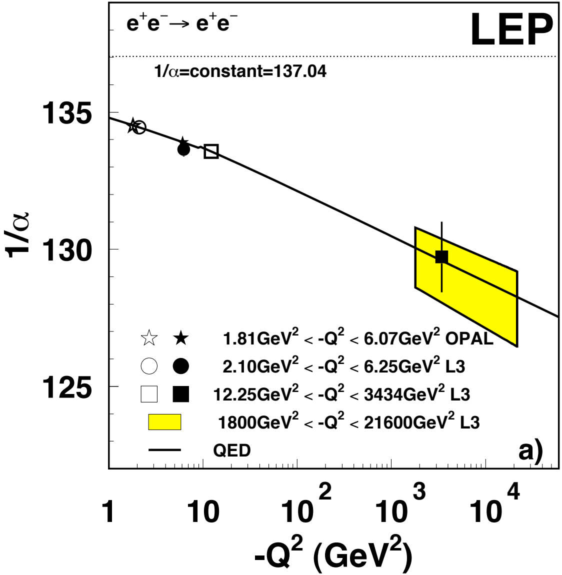


Charge screening in QED (electrons + photons)



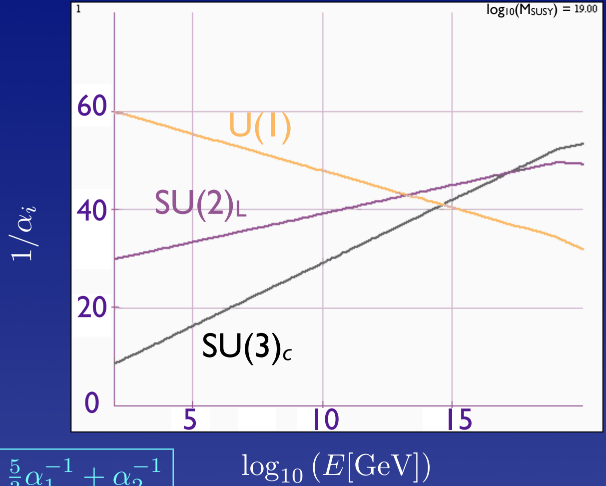
$$1/\alpha(Q) = 1/\alpha_0 - \frac{2}{3\pi}\ln\left(\frac{Q}{m}\right)$$

Charge screening in QED (real world)



Coupling Constant Unification

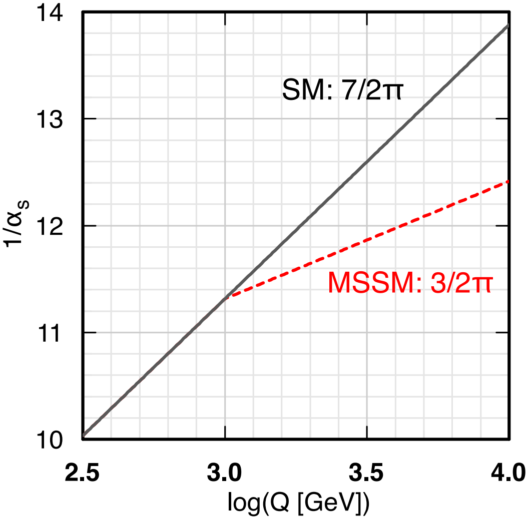
Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$
gives possibility of coupling constant unification



$$\boxed{\alpha^{-1} = \tfrac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}}$$

Can LHC See Change in Evolution?

Sensitive to new colored particles

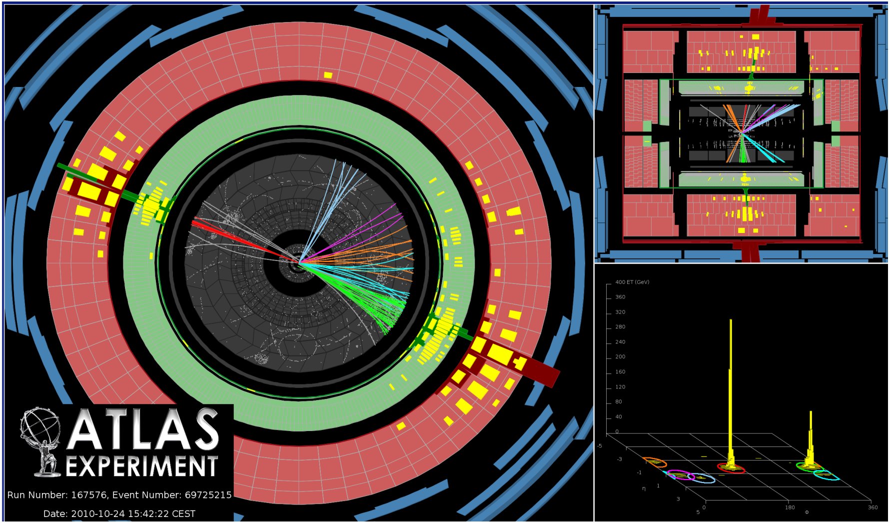


(sharp threshold illustrated)

. . . also for $\sin^2\theta_W$

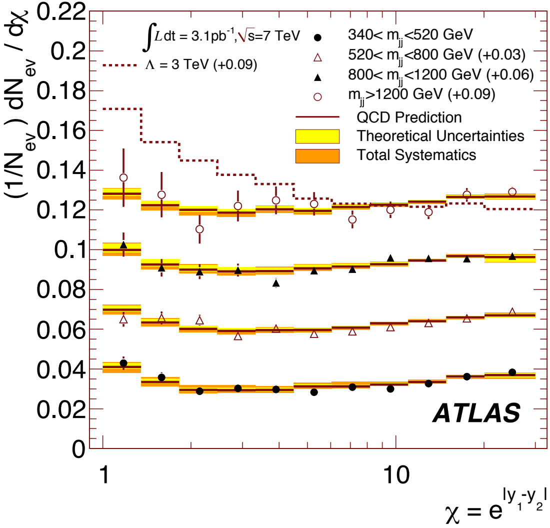
Most Violent Collision

The World's Most Powerful Microscopes



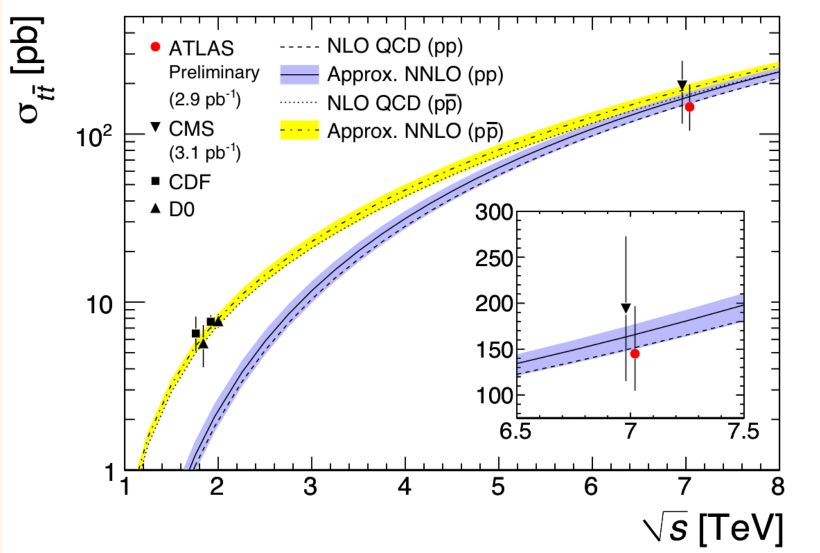
Transverse momenta: 1.3 TeV + 1.2 TeV

Search for Contact Interaction (Compositeness)

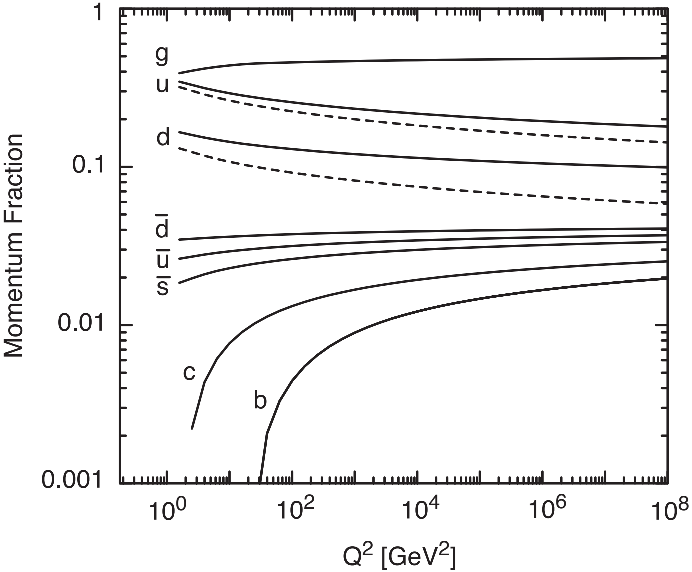


$$\boxed{3.1\ \mathrm{pb}^{-1} \rightsquigarrow \Lambda^* > 3.4\ \mathrm{TeV}}$$

First measurements of $\sigma(t\bar{t})$



Partition of Proton's Momentum



Small Exercise in QCD Evolution

By computing the $n = 2$ moments of the Altarelli-Parisi splitting functions in QCD,

$$A_n(q \leftarrow q) \equiv \int_0^1 dz\, z^{n-1} P_{q \leftarrow q}(z),$$

etc., project the momentum fractions of each parton species within the proton to $Q^2 \to \infty$. Show that

$$\begin{aligned}
\int_0^1 dx\, xG(x, Q^2 \to \infty) &= \tfrac{8}{17}, \\
\int_0^1 dx\, xq_s(x, Q^2 \to \infty) &= \tfrac{3}{68} \text{ (each flavor)}, \\
\int_0^1 dx\, xq_v(x, Q^2 \to \infty) &= 0.
\end{aligned}$$

XVI Escola Jorge Swieca

Potential Discoveries at the Large Hadron Collider

Chris Quigg

Fermilab

SM shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

Parameters of the Standard Model

3 coupling parameters: α_s, α_{EM}, $\sin^2\theta_{\mathrm{W}}$

2 parameters of the Higgs potential

1 vacuum phase of QCD

6 quark masses

3 quark mixing angles

1 CP-violating phase

3 charged-lepton masses

3 neutrino masses

3 leptonic mixing angles

1 leptonic CP-violating phase (+ Majorana)

$\geq$ 26 arbitrary parameters

Flavor physics . . .

may be where we see, or diagnose, the break in the SM

Some opportunities (see Buras, Flavour Theory: 2009)

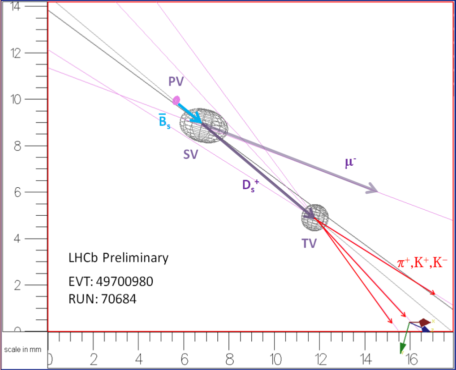
- CKM matrix from tree-level decays (LHC*b*)
- $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$
- D^0–$\bar{D}^0$ mixing; CP violation
- FCNC in top decay: $t \to (c, u)\ell^+\ell^-$, etc.
- Correlate virtual effects with direct detection of new particles to test identification
- Tevatron experiments demonstrate capacity for very precise measurements: e.g., B_s mixing.

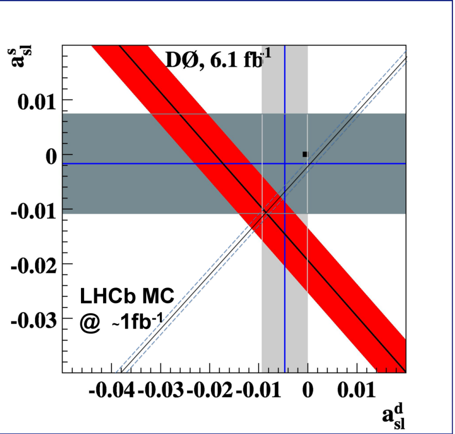
$\boxed{\text{All fermion mass is physics beyond the standard model!}}$

Hadron colliders are precision instruments!

LHC*b* Sequential Decay

begin to confront DØ surprise at 100 pb^{-1}





Stability bounds

Quantum corrections to $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$

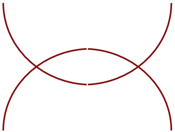
Triviality of scalar field theory bounds M_H from above

- Only *noninteracting* scalar field theories make sense on all energy scales
- Quantum field theory vacuum is a dielectric medium that screens charge
- $\Rightarrow$ *effective charge* is a function of the distance or, equivalently, of the energy scale

running coupling constant

Bounding M_H from above . . .

In $\lambda\phi^4$ theory, calculate variation of coupling constant λ in perturbation theory by summing bubble graphs



$\lambda(\mu)$ is related to a higher scale Λ by

$$\frac{1}{\lambda(\mu)} = \frac{1}{\lambda(\Lambda)} + \frac{3}{2\pi^2}\log\left(\Lambda/\mu\right)$$

(Perturbation theory reliable only when λ is small, lattice field theory treats strong-coupling regime)

Bounding M_H from above ...

For stable Higgs potential (*i.e.*, for vacuum energy not to race off to $-\infty$), *require* $\lambda(\Lambda) \geq 0$

Rewrite RGE as an inequality

$$\frac{1}{\lambda(\mu)} \geq \frac{3}{2\pi^2} \log(\Lambda/\mu)$$

... implies an *upper bound*

$$\boxed{\lambda(\mu) \leq 2\pi^2/3 \log(\Lambda/\mu)}$$

Bounding M_H from above ...

If we require the theory to make sense to arbitrarily high energies—or short distances—then we must take the limit $\Lambda \to \infty$ while holding μ fixed at some reasonable physical scale. In this limit, the $\boxed{\text{bound}}$ forces $\lambda(\mu)$ to zero.

$\longrightarrow$ free field theory "trivial"

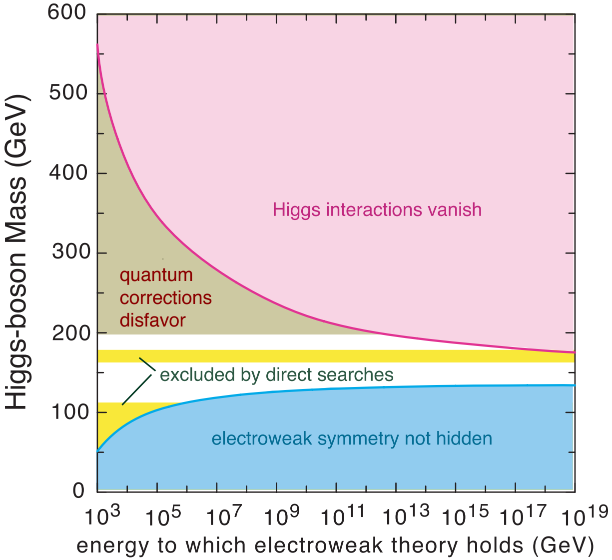
Rewrite as bound on M_H:

$$\Lambda \leq \mu \exp\left(\frac{2\pi^2}{3\lambda(\mu)}\right)$$

Choose $\mu = M_H$, and recall $M_H^2 = 2\lambda(M_H)v^2$

$$\boxed{\Lambda \leq M_H \exp\left(4\pi^2 v^2/3M_H^2\right)}$$

Bounding M_H from above ...



Bounding M_H from above . . .

Moral: For any M_H, there is a *maximum energy scale* $\Lambda^\star$ at which the theory ceases to make sense.

The description of the Higgs boson as an elementary scalar is at best an effective theory, valid over a finite range of energies

Perturbative analysis breaks down when $M_H \to 1\ \text{TeV}/c^2$ and interactions become strong

Lattice analyses $\Longrightarrow M_H \lesssim 710 \pm 60$ GeV if theory describes physics to a few percent up to a few TeV

$\boxed{\text{If } M_H \to 1 \text{ TeV EW theory lives on brink of instability}}$

Requiring $V(v) < V(0)$ gives *lower* bound on M_H

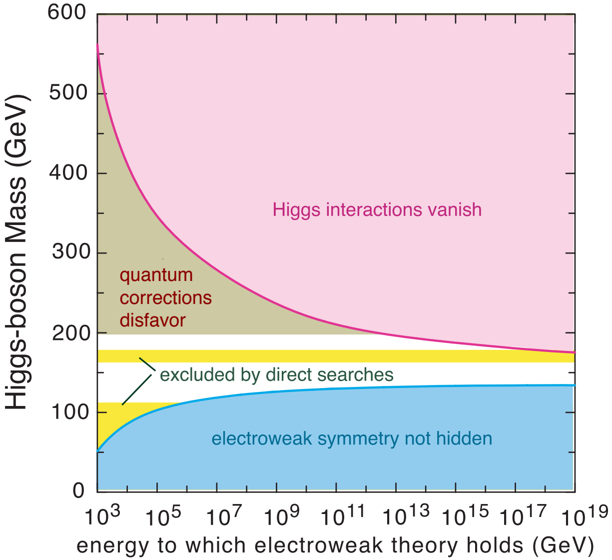
Requiring that $\langle\phi\rangle_0 \neq 0$ be an absolute minimum of the one-loop potential up to a scale Λ yields the vacuum-stability condition . . . (for $m_t \lesssim M_W$)

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2}(2M_W^4 + M_Z^4 - 4m_t^4)\log(\Lambda^2/v^2)$$

(No illuminating analytic form for heavy m_t)

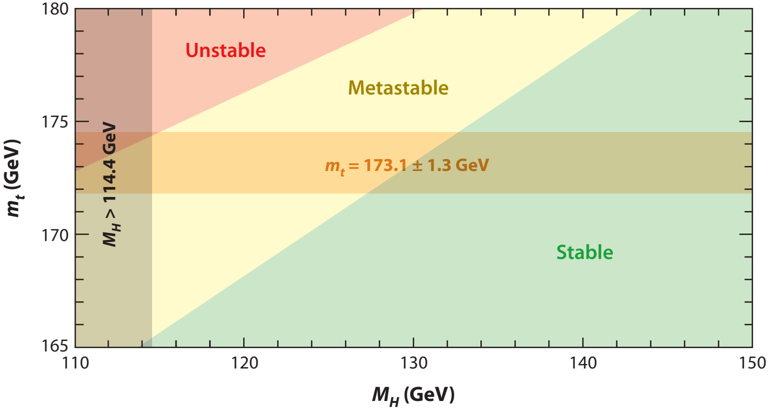
If Higgs boson is relatively light (which would require explanation) then theory can be self-consistent up to very high energies

Consistent to M_{Planck} if 134 GeV $\lesssim M_H \lesssim$ 177 GeV



Living on the Edge?

Require cosmological tunneling time, not absolute stability



Isidori, et al., hep-ph/0104016

Beyond the Standard Model
More physics on the TeV scale?

Partial-wave unitarity analysis of WW scattering argues for new physics on the TeV scale.
In SM: a Higgs boson or strongly interacting gauge sector
In general, something new on the TeV scale

At the level of suggestion, rather than theorem ...

- The hierarchy problem: if light H, new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses 0.1–1 TeV

The EW scale and beyond

EWSB scale, $v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246$ GeV, sets

$$M_W^2 = g^2 v^2/2 \qquad M_Z^2 = M_W^2/\cos^2\theta_W$$

But it is not the only scale of physical interest

natural: $M_{\text{Planck}} = 1.22 \times 10^{19}$ GeV

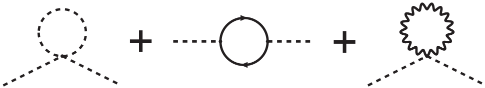
probable: $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ unification scale $\sim 10^{15-16}$ GeV

somewhere: flavor scale?

The Hierarchy Problem

Evolution of the Higgs-boson mass

$$M_H^2(p^2) = M_H^2(\Lambda^2) +$$



quantum corrections from particles with $J = 0, \frac{1}{2}, 1$

Potential divergences:

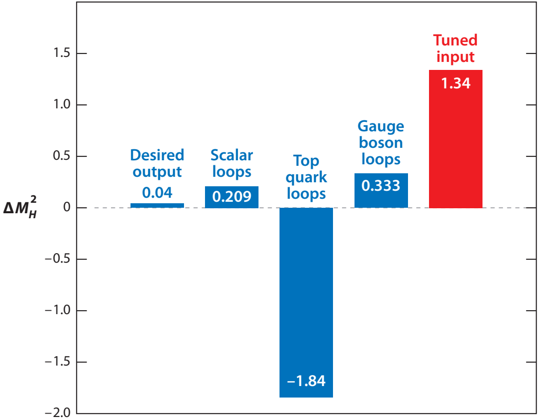
$$M_H^2(p^2) = M_H^2(\Lambda^2) + \mathcal{C}g^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots \;,$$

Λ: naturally large, $\sim M_{\text{Planck}}$ or $\sim U \approx 10^{15-16}$ GeV

How to control quantum corrections?

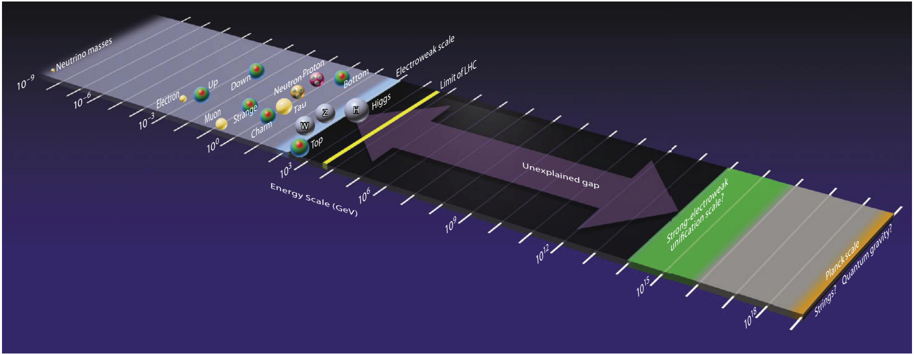
A Delicate Balance ... even for $\Lambda = 5$ TeV

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$



Light Higgs + no new physics: LEP Paradox

The Hierarchy Problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*
How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*
Why is the electroweak scale small?

The Hierarchy Problem
Possible paths

- Fine tuning
- A new symmetry (supersymmetry)
  fermion, boson loops contribute with opposite sign
- Composite "Higgs boson" (technicolor . . .)
  form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

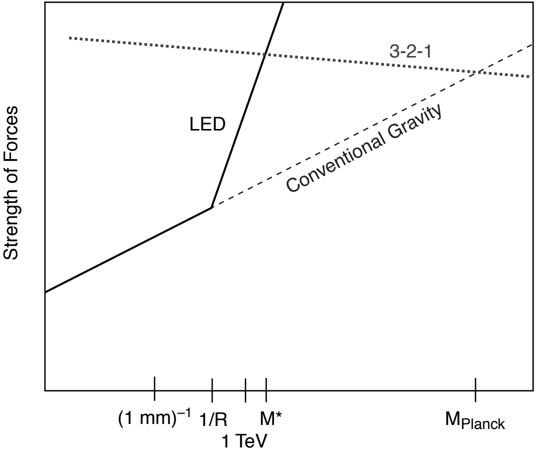
$\boxed{\text{All but first require new physics near the TeV scale}}$

Gravity at a Low Scale

At scale R ... gravity propagates in $4+n$ dimensions

$$1/r^2 \rightsquigarrow 1/r^{2+n}$$

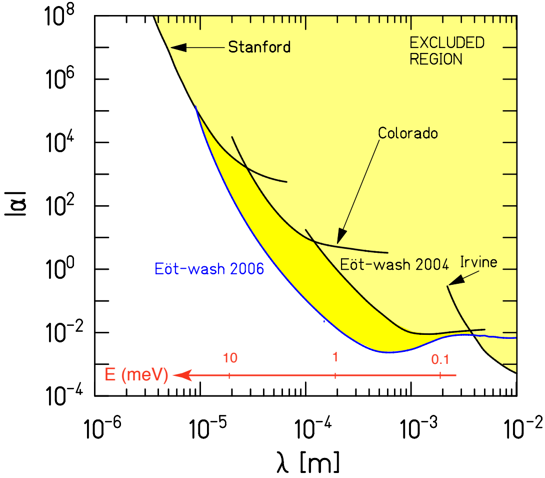
Gauss law: $G_\mathrm{N} \sim M^{*-n-2}R^n$ $\qquad$ M^*: gravity's true scale



M_{Planck} would be a mirage!

Gravity follows $1/r^2$ law to $\lesssim 1$ mm (few meV)

$$V(r) = -\int dr_1 \int dr_2 \frac{G_N \rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_G \exp(-r_{12}/\lambda_G)\right]$$



Some Recent Inventions

- In Little Higgs models, Higgs mass instability is canceled by particles of the same spin: e.g. spin-1/2 “heavy top”
  temporary solution, up to perhaps 10 TeV
- If a gauge (vector) field resides in 5D space, it appears to a 4D observer as 2 fields: spin-1 and spin-0
- “Higgsless” models: 5D incarnations of 4D technicolor
- Fourth generation of quarks and leptons ...

Supersymmetry

- A fermion-boson symmetry that arises from new *fermionic* dimensions
- Most general symmetry of S-matrix: SUSY + Poincaré invariance + internal symmetries
- Relates fermion to boson degrees of freedom: roughly, each particle has a superpartner with spin offset by $\frac{1}{2}$
- SUSY relates interactions of particles, superpartners
- Known particle spectrum contains no superpartners $\Rightarrow$ SUSY doubles the spectrum
- SUSY invariance or anomaly cancellation requires two Higgs doublets to give masses to $I_3 = \pm\frac{1}{2}$ particles

Why Supersymmetry?

- Closely approximates the standard model
- Maximal (unique) extension of Poincaré invariance
- Path to gravity: local supersymmetry $\longrightarrow$ supergravity
- Solution to naturalness problem: allows fundamental scalar at low E
- (+ unification) $\sin^2\theta_W$, coupling constant unification
- (+ universality) Can generate SSB potential
- (+R-parity) LSP as dark matter candidate

P. Fayet slides and video

Yukawa terms consistent with SUSY induce dangerous lepton- and baryon-number violations:

$$\lambda_{ijk} L^i L^j E^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda'' \bar{U}^i \bar{D}^j \bar{D}^k$$

45 free parameters ... Transitions like

$$\mathcal{L}_{LLE} = \lambda_{ijk}\, \tilde{\nu}^i_L e^i_L \bar{e}^k_R + \ldots$$

To banish these, impose symmetry under R-parity:

$$R = (-1)^{3B+L+S}$$

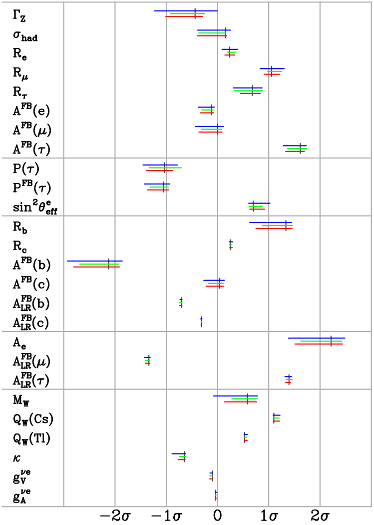
... even for particles, odd for superpartners.

Superpartners produced in pairs

Lightest superpartner is stable

5 physical Higgs bosons: CP even h^0, H^0; CP odd A^0; $H^\pm$

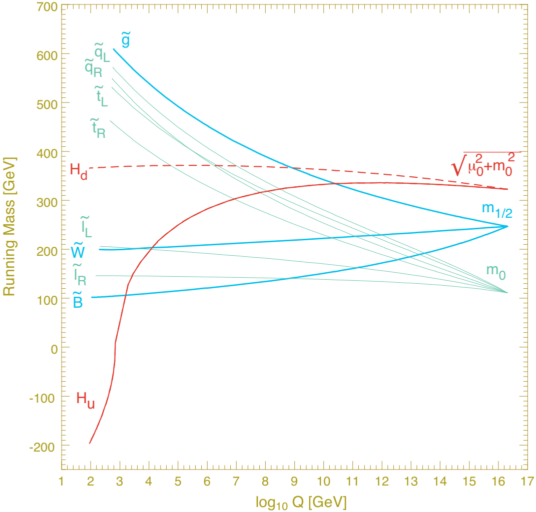
MSSM closely resembles standard EW theory



Erler & Pierce: SUSY *vs.* SM, hep-ph/9801238 Cho & Hagiwara, hep-ph/9912260

| SM — SUGRA — $5 \oplus 5^\star$ GMSB — $10 \oplus 10^\star$ GMSB

For heavy top, SSB may follow naturally in SUSY

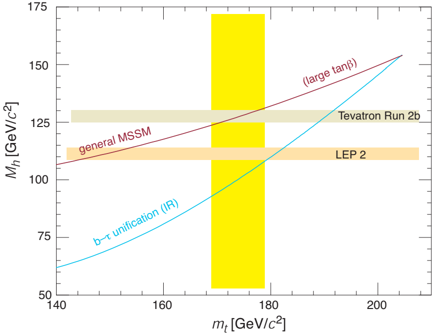


...(sign of M^2 indicated) Kane, *et al.* (hep-ph/9312272, *Phys. Rev. D***49**, 6173 (1994))

Upper bounds on M_h in the MSSM

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \cdots\right] \lesssim (130\ \mathrm{GeV}/c^2)^2$$

Upper bound on $M_h \Leftrightarrow$ large M_A limit, ($M_s = 1$ TeV)



Carena, *et al.*, *Phys. Lett.* **B355**, 209 (1995)

If nonminimal SUSY Higgs couplings are perturbative up to M_U,

$$\boxed{M_h \lesssim 150\ \mathrm{GeV}}$$

SUSY Challenges . . .

- Extra dynamics needed to break SUSY
  "Soft" SUSY breaking $\Longrightarrow$
  MSSM with $\boxed{124}$ parameters

  Contending schemes for SUSY breaking:
  - *Gravity mediation.* SUSY breaking at a very high scale, communicated to standard model by supergravity interactions
  - *Gauge mediation.* SUSY breaking nearby ($\lesssim$ 100 TeV), communicated to standard model by (nonperturbative ?) gauge forces.
  - . . .

  None meets all challenges

…SUSY Challenges

- Weak-scale SUSY protects M_H, but does not explain the weak scale ("μ problem")
- Global SUSY must deal with the threat of FCNC
- (Like SM) Clear predictions for gauge-boson masses, not so clear for squarks and sleptons
- So far, SUSY is well hidden Contortions for $M_H \gtrsim 115$ GeV
- (SUSY didn't relate particles & forces, but doubled spectrum)
- Baryon- and lepton-number violating interactions arise naturally, are abolished by decree

...SUSY Challenges

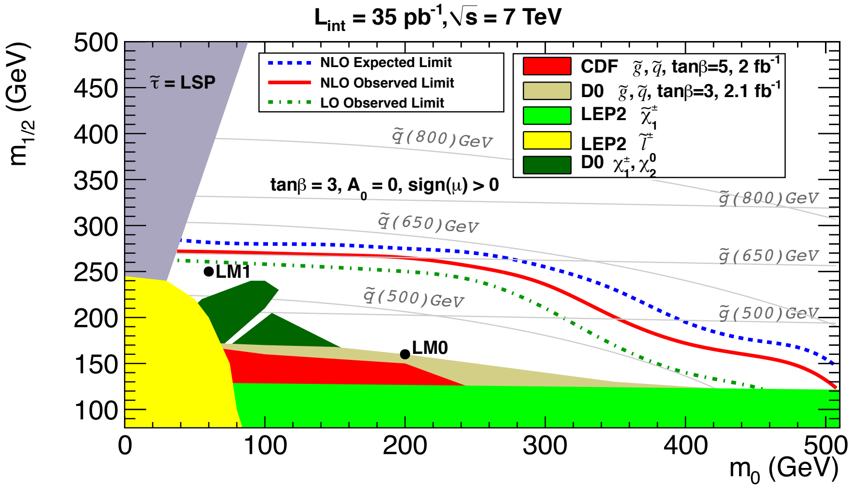
- SUSY introduces new sources of CP violation that are potentially too large. "Minimal flavor violation"
- We haven't found a convincing and viable picture of the TeV superworld.

This long list of challenges doesn't mean that Supersymmetry is wrong, or irrelevant to the 1-TeV scale.

But SUSY is not automatically right, either!

If SUSY operates on the TeV scale, Nature has found solutions to these challenges ...

Example: CMS SUSY Search

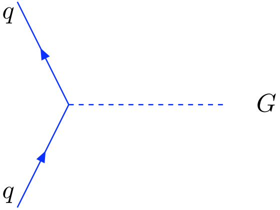


Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

Gravitational *ep* interaction $\approx 10^{-41} \times$ EM

$$G_{\text{Newton}} \textit{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV } \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

300 years after Newton: Why *is* gravity weak?

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda| (\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda| v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

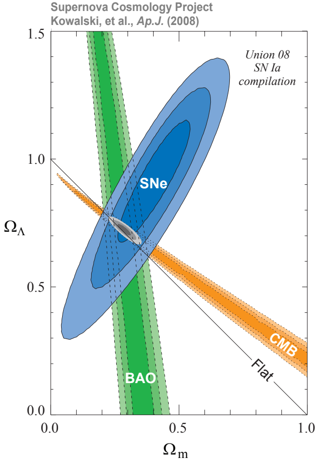
$V \neq 0$ contributes position-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4} \quad \approx 10^{24} \text{ g cm}^{-3}$$

Adding vacuum energy density $\varrho_{\text{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_N}{c^4}\varrho_{\text{vac}}$$

Observed $\varrho_{\text{vac}} \lesssim 10^{-46}$ GeV^4



$\varrho_H \gtrsim 10^8$ GeV^4: mismatch by 10^{54}

A chronic dull headache for thirty years . . .

More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the "Higgs boson" elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV?
- How can a light H coexist with absence of new phenomena?
- Is EWSB related to gravity through extra spacetime dimensions?

More Electroweak Questions for the LHC$^{\text{bis}}$

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of H?
- Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

More Electroweak Questions for the LHC$^{\text{ter}}$

- What will be the next symmetry recognized in Nature? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

In a decade or two, we can hope to …

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish neutrinos = antineutrinos
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, …)
Observe neutron's EDM, pursue electron's
Use top quark as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine the unifying symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly massless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

… learn the right questions to ask ...

… and rewrite the textbooks!

Thank you!

Good luck!

Mangano, CERN 2011

Sphicas, CERN 2011